

M. E. G. L.

BULLETIN of the American Association of Petroleum Geologists

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AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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WALTER A. VER WIEBE, *Editor*
GEOLOGICAL DEPARTMENT, UNIVERSITY OF WICHITA, WICHITA, KANSAS

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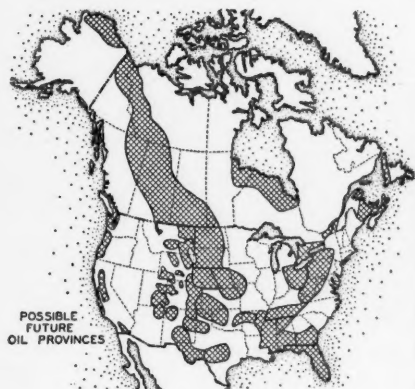
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Edited by A. I. Levorsen

A Symposium conducted by the Research Committee of the American Association of Petroleum Geologists, A. I. Levorsen, Chairman. Papers read before the Association at the Twenty-Sixth Annual Meeting, at Houston, Texas, April 1, 1941, and published in the Association Bulletin, August, 1941



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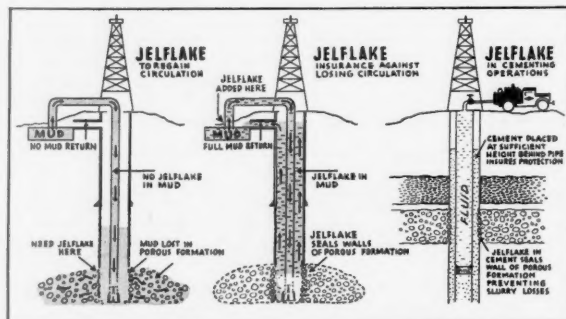
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PETROLEUM GEOLOGISTS**

SEPTEMBER, 1941

REGIONAL STRATIGRAPHY OF MID-CONTINENT¹

ROBERT H. DOTT²

Norman, Oklahoma

ABSTRACT

This paper considers the distribution, subdivision, and correlation of rock series from pre-Cambrian through Cretaceous, exposed in the region lying between the Llano uplift (Central Mineral region) of Texas, and the south line of South Dakota; and between the east line of New Mexico, and the Mississippi River, with some notes on their subsurface distribution and importance.

Pre-Cambrian igneous and metamorphic rocks, probably of Algonkian age, are exposed in six areas: Llano uplift, Texas; Wichita, Arbuckle, and Ozark mountains, Oklahoma; St. Francois Mountains, Missouri; and Sioux Falls district, South Dakota.

Great thicknesses of Upper Cambrian and Ordovician rocks, dominantly limestones, are exposed in the Llano uplift and the Arbuckle and Wichita mountains. The Ouachita Mountains, Oklahoma and Arkansas, present a sequence of Cambrian and Ordovician rocks, which, in common with all younger rocks of the area, are so different in lithologic character from rocks of adjacent areas, that direct correlations are difficult. Limestones, dolomites, and sandstones characterize Cambrian and Ordovician rocks exposed in the Ozark area of southern Missouri, northern Arkansas, and northeast Oklahoma; and of northeast Iowa. Important oil and gas production is found in Ordovician rocks in Reagan County, Texas, and in central Oklahoma and central Kansas.

Distribution of Silurian and Devonian rocks is much more restricted than the preceding, the sequence is incomplete in comparison with the standard New York section, and total thickness is small. Rocks of these systems crop out in the Arbuckle Mountains, Oklahoma; Ouachita Mountains, Oklahoma and Arkansas; Ozark Mountains, Oklahoma and Arkansas; southeast, central, and northeast Missouri; and northeast Iowa. Oil and gas production is found in the "Hunton" limestone, in Oklahoma and Kansas, and recently in southeast Nebraska.

For the purpose of this discussion the Mississippian and Pennsylvanian are classed as independent systems. The Mississippian is represented throughout most of the Mid-Continent region, but is best developed in the Ozark area of Oklahoma, Arkansas and Missouri, and in Iowa, where limestones are prominent constituents. It does not crop out in the Wichita Mountains, Oklahoma, and the section is very thin and incomplete in the Llano uplift, Texas. In the Arbuckle Mountains, Oklahoma, the section is dominantly black shale. The Mississippian in the subsurface is of great economic importance because of the large number and widespread distribution of oil and gas fields in Kansas and Oklahoma that produce from rocks of this age.

Pennsylvanian rocks are exposed in almost continuous outcrops from the north flank of the Llano uplift, Texas, to north-central Iowa, in a belt that trends with the regional strike. The Pennsylvanian section of the Mid-Continent is one of the thickest and most complete to be found in North America. This is particularly true of the development in Oklahoma and Kansas, and these Pennsylvanian rocks deserve considera-

¹ Presented before the Association at Oklahoma City, March, 1939. Manuscript received, January 29, 1941.

² Director, Oklahoma Geological Survey.

tion as a possible standard section. A four-fold division into Morrow, Des Moines, Missouri, and Virgil series seems applicable to exposures throughout the region. A new series called Lampasas, between Morrow and Des Moines, has been proposed for North Texas. Upper Pennsylvanian beds, particularly in central Oklahoma and North Texas, are characterized by redbeds. Pennsylvanian rocks underly the entire Mid-Continent region, west of the outcrops, and are very important because of the large number of oil fields, and large amounts of oil and gas that have been found in them.

The Permian is recognized as a system, and rocks of this age crop out in a belt parallel with, and west of, the Pennsylvanian. They are dominantly redbeds in North Texas and Oklahoma, but grade into marine sediments northward and southward. A recent standard classification, based on the marine section of southwest Texas, subdivides the Permian into Wolfcamp, Leonard, Guadalupe, and Ochoa series, and the lower three have been correlated into the area under consideration. Oil and gas production in Permian rocks is important in West Texas, the Texas and Oklahoma panhandles, southwestern Kansas, and some southern Oklahoma fields.

Upper Triassic rocks are exposed only along the east margin of the high plains, in Texas; in Texas and Cimarron counties, Oklahoma; and in Morton County, Kansas. Jurassic beds are well exposed in Cimarron County, Oklahoma, and are mapped in adjacent areas. A salt-redded section found by recent drilling in Ouachita County, Arkansas, has been assigned to the Jurassic.

The Cretaceous is widespread in the south, west, and northwest parts of the region. In north and northeast Texas, and adjacent parts of Oklahoma, the Cretaceous is divided into the Comanche and Gulf series. In Cimarron County, Oklahoma, only the upper part of the Comanche is present, most of the section belonging to the lower part of the Gulf series. In Kansas, a little of the upper Comanche is mapped with the Dakota sandstone, but most of the section in Kansas, Nebraska, and northwestern Iowa belongs to the Gulf series. Comanche rocks produce oil and gas in Arkansas, and northwest Louisiana, and in south-central Texas; and beds belonging to the Gulf series are important producers in central and East Texas, as well as in Louisiana and Arkansas.

INTRODUCTION

The following maps and charts are presented to show the distribution, sequence, and major subdivisions of the rocks of the different systems that crop out and are found by drilling in various parts of the Mid-Continent region. The data are compiled almost wholly from the literature, and reflect the writer's best judgment in interpreting the literature examined, with the benefit of criticism and corrections by specialists on the different periods and areas, to whom the manuscript was submitted. Credit to these collaborators is gratefully acknowledged.

The geologic map of the United States, compiled by George W. Stose and O. A. Ljungstedt, published by the United States Geological Survey in 1932, was used as the base for preparing the maps. Outcrops were taken mainly from this map, with some modifications from other sources.

Outcrops and other data for rocks of the pre-Cambrian, the Paleozoic systems, and the Mesozoic are shown on individual maps, and numbers adjacent to outcrop areas give a cross-reference to the stratigraphic sections shown in the corresponding charts.

Liberal use was made of the charts prepared by Shimer,³ though

³ H. W. Shimer, "Correlation Chart of Geologic Formations of North America," *Bull. Geol. Soc. America*, Vol. 45 (1934), pp. 909-36.

his correlations were modified in detail, on the basis of information obtained from other literature, listed in the bibliographies, to which reference is made at the proper place.

Correlations of formations exposed in areas so widely separated are subject to change; hence, such a compilation as this can be regarded as nothing more than a progress report. The writer has endeavored to bring together the best information on the subject, and hopes that the material will prove useful to geologists interested in the stratigraphy of the Mid-Continent region.

The Mid-Continent region, for the purpose of this discussion, is defined as the area between the Llano uplift of Texas, and the south line of South Dakota; and between the east line of New Mexico and the Mississippi River. It includes parts of Texas and Arkansas, most or all of Oklahoma, Missouri, Kansas, Nebraska, and Iowa.

The rocks considered range in age from pre-Cambrian to the base of the Cenozoic.

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FIG. 1.—Distribution of pre-Cambrian rocks in Mid-Continent region. Solid areas indicate outcrops. Circles indicate drill holes in which pre-Cambrian rocks were found at depths less than 6,000 feet. Stippling indicates oil fields in which pre-Cambrian has been found by drilling over considerable areas. Numbers correspond with areas listed in Chart I.

PRE-CAMBRIAN

1 LLANO UPLIFT (CENTRAL MINERAL)	2 ARBUCKLE AREA		3 WICHITAS	4 OKLAHOMA OZARKS	5 ST. FRANCOIS	6 SOUTH DAKOTA
	TISHOMINGO UPLIFT	ARBUCKLE ANTICLINE				
UPPER CAMBRIAN	UPPER CAMBRIAN	UPPER CAMBRIAN	UPPER CAMBRIAN	ORDOVICIAN	UPPER CAMBRIAN	CRETACEOUS
GRANITES, ETC.	TISHOMINGO GRANITE	COLBERT PORPHYRY	GRANITE- PORPHYRY QUANAH LUGERT SADDLE MT. CARLTON DAVIDSON GABBRO- ANORTHOSITE	SPAVINAW GRANITE	RHYOLITE, GRANITE- PORPHYRY, AND GRANITE	
	?	?		?	?	?
LLANO SERIES PACKSADDLE SCHIST VALLEY SPR. GNEISS			MEERS QUARTZITE			SIoux QUARTZITE

CHART I.—Subdivisions and nomenclature of pre-Cambrian rocks in different outcrop areas. Arrangement in each area indicates relative age, oldest at bottom. Exact age and correlations between different areas not known.

subsurface stratigraphy of Kansas; to Hugh D. Miser, for comments on the Pennsylvanian, particularly of the Ouachita Mountains; to Raymond C. Moore, for comments on the Pennsylvanian of the northern Mid-Continent; and to C. W. Tomlinson, for invaluable help on the Pennsylvanian of the Ardmore basin, and for the privilege of reading an unpublished manuscript.

PRE-CAMBRIAN

Igneous and metamorphic rocks assigned to the pre-Cambrian are exposed in six different parts of the region: Llano uplift of Texas; Tishomingo and Arbuckle anticline (Timbered Hills) districts of the Arbuckle Mountains, Wichita Mountains, and Spavinaw district, all in Oklahoma; St. Francois Mountains, Missouri; and near Sioux Falls, South Dakota.

The arrangement of the names of units in the pre-Cambrian chart is not intended to indicate time equivalence, but rather the relative age of the units exposed in each area of outcrop. According to Van Hise and Leith (1),⁴ the rocks in the Sioux area of South Dakota and Minnesota are Algonkian in age, those in Texas and Missouri are Algonkian (?), and those in Oklahoma are unclassified.

Llano uplift, Texas.—Metamorphics belonging to the Llano series represent the oldest rocks in this area, and are intruded by younger granites and more basic rocks including diorite and gabbro. The pre-Cambrian is overlain, unconformably, by rocks of upper Cambrian and Cretaceous age (2).

Arbuckle Mountains, Oklahoma.—The pre-Cambrian is represented in the eastern or Tishomingo area by the Tishomingo granite which is intruded by small dikes of diabase, granite-porphyry, and aplite. These rocks are unconformably overlain by upper Cambrian and Cretaceous.

In the western or Arbuckle anticline (Timbered Hills) area, it is represented by the Colbert porphyry, which is overlain unconformably by upper Cambrian.

Wichita Mountains, Oklahoma (3, 4).—The metamorphic Meers quartzite is the oldest known rock in Oklahoma. It is exposed in only three small outcrops, and is intruded by anorthosite-gabbro in two, and by granophyre in the third. The relative age of pre-Cambrian units in the Wichitas was determined by Hoffman (5). These rocks are overlain, unconformably, by upper Cambrian and Permian sediments.

Merritt and Ham (6) have recently discovered another pre-Cam-

⁴ Numbers in parentheses indicate references at end of article.

brian sedimentary formation, composed of zeolite, opal, calcite, and dolomite, exposed near Tepee Creek (from which it is named), in western Kiowa County. Similar material is exposed 10-15 miles farther southeast, between Cold Springs and Mountain Park.

The strata appear to be horizontal, rest unconformably on anorthosite, and were formerly believed to be Permian limestone. In the type area they were found to be cut by a granitic dike, thus suggesting, if not proving, the pre-Cambrian age of the Tepee Creek formation. There is no direct evidence to indicate the age of the material in exposures near Cold Springs.

This discovery provides an important chapter in the pre-Cambrian history of the Wichitas, for the anorthosite cooled at great depth, was uplifted and eroded before deposition of the zeolite rock. Both were then intruded by the dike before igneous activity ceased.

Spavinaw district, Oklahoma.—Several small exposures of what is now generally regarded as pre-Cambrian granite, are found a few hundred yards below the dam on Spavinaw Creek, near the town of Spavinaw, Mayes County. It was originally thought by Drake (7) to be a dike that intruded into Ordovician rocks during a period of folding postulated as post-Carboniferous. The Spavinaw granite is overlain with great unconformity, by Lower Ordovician dolomite.

St. Francois Mountains, Missouri.—Pre-Cambrian rhyolite porphyry, granite porphyry, granite, and basic dikes are exposed in the St. Francois Mountains district of southeastern Missouri. They are overlain unconformably, by upper Cambrian and early Ordovician rocks (8).

Sioux Falls district, South Dakota.—In the vicinity of Sioux Falls, southeastern South Dakota, and adjacent parts of Minnesota and Iowa, is reddish, vitreous quartzite, somewhat conglomeratic, with pebbles of chert and jasper, and with associated quartz slate. Hayden (9) reported that the pipestone bed on Pipestone Creek, southwestern Minnesota, is associated with the quartzites, and is undoubtedly of the same age. The pre-Cambrian of this district is overlain, with great unconformity, by the Cretaceous.

Pre-Cambrian in subsurface.—The pre-Cambrian surface is sufficiently shallow in many parts of the Mid-Continent area, that it has been reached by the drill in exploring for oil and gas, and wells that have encountered pre-Cambrian rocks are shown by circles on the map. The distribution of these wells indicates probable structural features in the basement rocks, that are definitely present in Paleozoic rocks, and many of these have had important oil and gas fields developed upon them.

Four distinct features are indicated by the position of wells reaching pre-Cambrian in Texas: the subsurface extension of the Llano uplift in all directions; the Pecos uplift; the Red River uplift; and the Amarillo uplift, which is the westward extension of the Wichita Mountains axis (2).

Three features of the pre-Cambrian surface in Oklahoma are worthy of note: the western extension of the Wichita Mountains, and their connection with the Amarillo uplift (10); the southeast extension of the Arbuckle Mountains (11, 12); the northeastern "platform" area, whose pre-Cambrian surface is shallow, and rises in local, relatively sharp peaks, or is folded, with the overlying sedimentary rocks, into small, sharp domes (13). The Cushing oil field is located on a somewhat elongate example of the last type of structure.

In a test well drilled in Washington County, Arkansas, the pre-Cambrian was reached at a depth of 2,485 feet (14).

Two prominent features are shown in Kansas (15, 16); the Nemaha "granite ridge," trending southwest from southeastern Nebraska, into north-central Oklahoma; and the Central Kansas uplift-Chautauqua arch, which trend almost at right angles to the Nemaha feature. According to Koester (17),

Studies of pre-Cambrian wells show that the "ribs" or structurally higher parts of the Central Kansas uplift are underlain by granite and quartzite, while the pre-Cambrian rocks are schists in the saddle between the ribs, and on the flanks of the uplift.

Evidence from samples from deep wells presented by McQueen (18) indicates a buried ridge on the pre-Cambrian floor along the west line of Missouri.

Features revealed by the shallow depths at which pre-Cambrian rocks have been found in Nebraska, Iowa, and South Dakota are doubtless related to features already described: the Nemaha "ridge" in southeastern Nebraska and southwestern Iowa; the Cambridge anticline and Chadron dome, in southcentral and northwestern Nebraska, respectively; and the Sioux Falls uplift, in northeast Nebraska, southeast South Dakota and northwest Iowa (19).

PALEOZOIC ROCKS

CAMBRIAN AND ORDOVICIAN

Ulrich⁵ in 1911 revised the Paleozoic systems, and divided the rocks then called Cambrian and Ordovician, into four systems: Cambrian, Ozarkian, Canadian, and Ordovician. He combined the upper

⁵ E. O. Ulrich, "Revision of the Paleozoic Systems," *Bull. Geol. Soc. America*, Vol. 22 (1911).

third of the upper Cambrian and the basal formation of the Lower Ordovician into Ozarkian, and assigned the remainder of the Lower Ordovician to the Canadian.

Though Ulrich's classification has some merit in certain areas, it has not been generally accepted by stratigraphers, and for the purposes of this discussion, the more conventional classification of Cambrian and Ordovician is followed.

CAMBRIAN

Rocks of upper Cambrian age are exposed in the Llano uplift of Texas; in the Arbuckle and Wichita mountains, Oklahoma; in the Ouachita Mountains of southeast Oklahoma and southwest Arkansas; in the St. Francois-Ozark region of Missouri; and in the northeast corner of Iowa. In all these outcrops, the base of the Cambrian, where exposed, rests unconformably on the uneven pre-Cambrian surface. In northeast Oklahoma the Cambrian is overlapped by Lower Ordovician beds, which are in contact with the pre-Cambrian. Cambrian rocks are not exposed in the Ozark area of Arkansas, but are encountered in deep drilling.

In Texas and south-central and southwestern Oklahoma, the Cambro-Ordovician boundary falls within thick limestone units (Ellenburger and Arbuckle) and the division has been based largely on paleontologic evidence, though Bridge (1) has recently presented evidence for making a lithologic separation. This boundary has not been mapped in the field, and the contacts with younger beds are only approximately shown in Figure 2.

In the Ouachita Mountains rocks of all the Paleozoic systems, including the Cambrian, exemplify lithologic facies that are quite distinct from those of the rocks exposed elsewhere in the Mid-Continent area, and most closely resemble the rocks found in the Marathon area of southwest Texas. This difference in facies between rocks of the same age, in close geographic proximity, is discussed by van der Gracht (2).

Llano uplift, Texas.—The Cambrian of the Llano uplift is summarized by Sellards, Adkins and Plummer (3), and is divided into the following units, listed in ascending order: Hickory formation, consisting prevailingly of conglomerate or sandstone, resting on the unevenly eroded surface of pre-Cambrian schists, gneiss, and granites, and grading upward into the glauconitic sands and limestones of the Cap Mountain; Cap Mountain formation, mainly glauconitic limestone, containing the Lion Mountain sandstone member (4) at its top; Wilberns formation, consisting of limestone with some shale, and locally lime-



FIG. 2.—Distribution of Cambrian rocks in Mid-Continent region. Solid areas denote outcrops. Heavy, broken lines with queries indicate probable limits of subsurface distribution. Numbers correspond with areas listed in Chart II.

CAMBRIAN

	1	2-3	4-5	6	7
	LLANO UPLIFT	WICHITAS-ARBUCKLES	OUACHITAS	OZARKS	N. E. IOWA
ORDOVICIAN	UPPER ELLENBURGER	UPPER ARBUCKLE MC KENZIE HILL FM.	CRYSTAL MT. SS.	VAN BUREN	ONEOTA
	LOWER ELLENBURGER	BUTTERLY DOL. SIGNAL MT. ROYER DOL. ? FT. SILL LS.	?	EMINENCE POTOSI	TREMPEALEAU
CAMBRIAN	WILBERNS FM.	HONEY CREEK LS. REAGAN FM.	COLLIER SH. ?	DOE RUN DERBY DAVIS	FRANCONIA (NOT EXPOSED)
	LION MT. MEM. CAP MT. FM.			BONNETERRE	
	HICKORY			LA MOTTE	DRESBACH (NOT EXPOSED)

CHART II.—Subdivisions, nomenclature, and best available correlations of Cambrian rocks in different areas.

stone conglomerates, and containing beds at the top that were formerly classed as Ellenburger, and which contain fossils common to the Fort Sill formation of Oklahoma (4); lower Ellenburger, consisting of coarsely crystalline, cherty and dolomitic limestone in the basal part, that contains a fauna similar to the Potosi of Missouri, and finely crystalline, cherty dolomite in the upper part, that contains fossils of the Eminence formation of Missouri. The Potosi-Eminence faunas are also found in the Signal Mountain formation of Oklahoma (5). The top of the Cambrian falls in the Ellenburger limestone.

Wichita Mountains, Oklahoma.—The Cambrian of the Wichita Mountains has recently been described by Decker (6, 7, 8), where he recognizes the following units, given in ascending order: Reagan formation, Honey Creek formation, Fort Sill formation, Royer dolomite, and Signal Mountain formation.

In a single exposure in the Wichita Mountains, Decker found 98 feet of limestone at the base of the Paleozoic section, which he regarded as distinct from, and older than, the Reagan formation. Because of the limited known outcrop and the lack of fossil evidence to determine age, it is here included with the Reagan formation.

The Reagan formation consists principally of sandstone, arkose, and conglomerate, with some limestones, and rests on the uneven pre-Cambrian surface. In many places it is glauconitic, and in one locality contains an appreciable concentration of hematite. There is commonly a gradation zone between the Reagan and the overlying Honey Creek. It is considered by Bridge to be equivalent to the Lion Mountain sandstone member of the Cap Mountain formation of Texas (9).

The Honey Creek formation in most places rests directly on the Reagan, though in some exposures it overlaps the Reagan, and rests on the pre-Cambrian, and includes fragments of igneous rocks. It is composed principally of limestone, and is correlated with the lower half of the Wilberns of Texas. The Honey Creek has been included with the Arbuckle by some authors, but Taff originally grouped it with the Reagan, and Decker now proposes to group the "basal limestone," Reagan, and Honey Creek formations into his Timbered Hills group.

The Fort Sill is a limestone formation made up mostly of thin beds, and containing some oölites and sponge spicules. It rests conformably on the Honey Creek formation, but is marked by an hiatus at the top, at least locally at Fort Sill, where the next younger Royer dolomite is absent, and the Fort Sill formation is followed by the Signal Mountain conglomeratic limestone. The Royer dolomite is 200 feet thick on the

northeast flank of the Wichita Mountains. The Signal Mountain consists of thin beds of limestone and some conglomerates. These latter are additional indication of an hiatus at the base. The Butterly formation, which occurs at the top of the Cambrian part of Decker's Arbuckle group, in the Arbuckle Mountains, is absent in the Wichita Mountains, and the Signal Mountain is unconformably succeeded by the McKenzie Hill, the lowest Ordovician formation.

As already indicated, Bridge has found Fort Sill fossils in the upper third of the Wilberns formation of Texas, as redefined by him. Apparently there is no equivalent, in the Wichitas, of the lower Ellenburger of Texas, which Bridge found to contain Potosi and Eminence faunas.

Evidence obtained from graptolites has led Decker to believe that the Cambro-Ordovician boundary belongs somewhat higher in the Arbuckle group than the base of the McKenzie Hill formation, but he is accepting, with reservations, the opinion of Bridge (10), and others, which is based on the evidence of other invertebrates, found along U. S. highway 77, in the Arbuckle Mountains.

Arbuckle Mountains, Oklahoma.—The Cambrian succession in the Arbuckle region, with one exception, is similar to that in the Wichitas. The Reagan rests on the uneven pre-Cambrian surface, and is succeeded, in turn, by the Honey Creek, Fort Sill, Royer, and Signal Mountain formations.

The Fort Sill locally contains arkosic material. The Fort Sill, Royer, and Signal Mountain formations are well represented in the area. Above the Signal Mountain, at the top of the Cambrian as now established, is the Butterly dolomite, which Bridge suggests may be part of the Signal Mountain (5). This unit is absent in the Wichita Mountains. The Signal Mountain and Butterly are probably to be correlated with the Potosi-Eminence of Missouri, and the lower Ellenburger of Texas (5).

Ouachita Mountains, Oklahoma and Arkansas.—The Cambrian is represented in the Ouachita Mountains by the Collier shale, which consists of bluish black, graphitic, clay shale (11, 12). The Collier is succeeded by the Crystal Mountain sandstone, which is conglomeratic at the base, and it in turn, by the Mazarn shale, which contains fossils of Lower Ordovician age. This stratigraphic relationship, the lack of lithologic similarity between the Collier and higher beds, and the evidence of the overlying conglomerate in establishing an unconformity at the top, are reasons for classifying the Collier as Cambrian. As already stated, the lithologic character of the Paleozoic rocks in the Ouachita Mountains is wholly unlike their equivalents in other parts of the Mid-Continent area.

St. Francois-Ozark Area, Missouri.—Cambrian rocks are exposed on the flanks of the St. Francois Mountains, southeast Missouri, and in the central Ozarks. The succession in these areas, and the correlation of units with the section in Texas, are given by Bridge (4). The succession in ascending order, is as follows: LaMotte sandstone, an arkosic, conglomeratic sandstone, which, in areas where the base is exposed, rests on the irregular pre-Cambrian surface. It is essentially equivalent to the Hickory formation of Texas. The contact with the overlying Bonnetterre dolomite is believed to be gradational, and Bridge indicates that the Bonnetterre is equivalent to the Cap Mountain and the uppermost Hickory. The succeeding Davis formation, Derby, and Doe Run dolomites have faunas represented in the Wilberns of Texas, and hence are correlated with the Honey Creek and Fort Sill limestones, of Oklahoma. The highest Cambrian units of Missouri are the Potosi and Eminence dolomites, whose faunas occur in the lower Ellenburger of Texas, and this interval is probably represented by the Royer dolomite, Signal Mountain formation, and Butterly dolomite of the Arbuckle Mountains, Oklahoma (5). The Proctor dolomite is considered by Bridge (4) to be the upper part of the Eminence formation in certain areas, while others regard it a distinct formation.

Northeast Iowa.—The lower Paleozoic section of the upper Mississippi Valley has been described by various authors (13). In Iowa, the Dresback, equivalent to the LaMotte and Bonnetterre, and the Franconia, equivalent to the Davis, Derby, and Doe Run, of Missouri, are not exposed and only the uppermost Cambrian, the Trempealeau, is represented. This is equivalent to the Potosi and Eminence, hence to the lower Ellenburger, of Texas, and Royer, Signal Mountain, and Butterly of Oklahoma.

Cambrian in subsurface.—The subsurface position of the Cambrian in North Texas and southern Oklahoma is imperfectly known, because relatively few wells have penetrated so deeply, and because the Cambro-Ordovician elements of the Ellenburger and Arbuckle limestones are difficult to differentiate. According to Sellards, Adkins, and Plummer (3), Cambrian rocks are absent in the Panhandle region of Texas, and in parts of Pecos and Foard counties. No data are available to indicate the areal extent of Cambrian sediments in southern and central Oklahoma, but their presence and thickness in the Arbuckle and Wichita Mountains suggests that they are present in a considerable part of the surrounding area.

The absence of Cambrian strata between the Cotter dolomite of Ordovician age, and pre-Cambrian granite in the Spavinaw district,

and the absence or thin representation of the "siliceous lime" above the pre-Cambrian, in drill holes in Pawnee, Osage and Rogers counties (14) indicates the probable absence of the Cambrian in northeastern Oklahoma.

According to Croneis (15) Cambrian rocks have been recognized in a few deep wells drilled in northwest Arkansas.

Studies of insoluble residues from well cuttings by McQueen (16) show that the entire Cambrian is absent near Rinehart, Vernon County, Missouri, where the Van Buren formation of Lower Ordovician age, rests on pre-Cambrian. In several other wells in western Missouri, between Jackson and Jasper counties, an important break occurs within the upper Cambrian, so that the Davis, Derby, Doe Run, and Potosi formations are absent, and the upper part of the Eminence rests directly on the Bonnetterre. Cuttings from a drill hole at Fredericktown, Madison County, near the St. Francois Mountains, indicate a similar hiatus, for here the Potosi rests directly on the Bonnetterre, with the Davis, Derby, and Doe Run absent. In the Eminence region, the Potosi rests on Bonnetterre at one locality, and on pre-Cambrian at many others (17). Elsewhere, at least in southern Missouri, the regular succession of Cambrian appears to be present (16, 18).

Koester (19) cites evidence to show that "... the unconformities which are known in the Ozarks occur in western Missouri and eastern Kansas." The unconformity of principal interest in this connection is the one at the base of the Potosi. According to Koester

... In a Chautauqua County well, McQueen has found a basal, sandy, arkosic phase of the Eminence overlying the Bonnetterre dolomite, with the Potosi, Derby-Doe Run, and Davis missing. ... In Butler County, Van Buren dolomite overlies pre-Cambrian rocks. Other information from McQueen and other geologists supports the view that as one follows the "Siliceous lime" westward from the Ozark region the lower portions are missing so that younger deposits overlap, and rest on pre-Cambrian rocks. The upper portion of the "Siliceous lime" in the Voshell field of McPherson County has been identified as Cotter. Lerke and others have found Cotter and Jefferson City beds in the upper portion of the "Siliceous lime" in wells within the nuclear area of the uplift where the "Siliceous lime" is much thinner than on the flanks. Ozarkian beds have been found under Canadian and above pre-Cambrian in a deep well in Barber County by McQueen ...

In a recent communication, Koester (20), comments as follows.

Glauconitic sands and sandy dolomites which are similar to Bonnetterre and Lamotte have been found in many wells scattered through Kansas, and have been conspicuous by their absence in other wells. Where a long section of Arbuckle has been drilled these beds are always in the lower portion of the section. We call them "Cambrian." At the top of the Arbuckle section, where "long sections" (400 to 1,000 feet) are drilled, we have dolomites and sandy

dolomites carrying the characteristic oölites of the Canadian and we make arbitrary distinctions between these upper beds and the intermediate part of the section, which we call "Ozarkian," believing that we are using approximately that part of the section which Ulrich defined as such, in each case. Therefore in deep tests to the pre-Cambrian off the "ribs" of the Uplift we think we can make a three-fold division of the Arbuckle.

Continuing, Koester generalizes as follows.

(1). The Canadian is nearly always present at the top of the Arbuckle section. It also persists in thickness more than the "Ozarkian" or "Cambrian."
(2). In many areas, if the Canadian is stripped off, the Ozarkian is also gone.
(3). Southeastern and south-central Kansas apparently have an almost complete section wherever the Arbuckle has been drilled.
(4). Different parts of the Central Kansas Uplift and probably different parts of the Nemaha ridge experienced different overlap relationships. In other words the overlaps are local not regional, except (5) in northwest Kansas and southwest Nebraska, the Canadian seems to be missing, and probably the Ozarkian as well, since several wells apparently find the Pennsylvanian resting directly on Cambrian . . . I wish to correct the impression [stated in his article in the *Bulletin*, 1935] that the Cambrian (in the larger and most commonly-accepted sense) is confined to southeastern Kansas. The overlap idea mentioned in the paragraph you quote, however, is still good.

Regarding the "basal sand," Koester continues,

. . . we can say with more assurance than in 1935, that some of it is Canadian in age. However, we also know that some of it is truly Lamotte, contrary to the statement I made in the *Bulletin* in 1935. ("Its correlation on the uplift with the Reagan and Lamotte is therefore untenable.") Inasmuch as we find a close relationship between the thickness of the "basal sand" and the presence or absence of quartzite in the pre-Cambrian complex, I am still of the opinion that much of the "basal sand" of the Russell rib is Canadian. However, on the Rush rib it is probably Cambrian in age . . . Very often no true basal sand is found. It is a very sandy dolomite, . . .

Available subsurface data indicate that the Cambrian is represented in Nebraska, except locally, as on the Nemaha granite ridge, and possibly at Lincoln.

According to Lugn (21),

The Cambrian and Ordovician systems, west of the Nemaha ridge, change somewhat in lithology and lose to some extent their identity with Iowa formations, and resemble more the Cambro-Ordovician rocks of Oklahoma (Arbuckle section-Reagan sandstone to Sylvan shale interval). The Cambrian sandstone on the Cambridge anticline has been referred by some to the Deadwood formation of the Black Hills. The Deadwood formation is recognized in the Duthie well northeast of Chadron.

The Cambrian appears to be present in the subsurface throughout Iowa (22), though some of the units may be locally absent, and the sandstone units are important sources of underground water supplies

for many cities. Saline waters, showing in excess of 900 parts per million of chloride, are found in the Cambrian at McGregor and in the vicinity of Davenport.

The entire Cambrian section known in outcrops of adjacent areas, including the Dresbach, Franconia, and Trempealeau formations, is recognized in the subsurface of Iowa.

ORDOVICIAN

Rocks of Ordovician age are exposed in the same areas as the Cambrian but with considerably larger outcrops: in the Llano uplift, Texas; Wichita and Arbuckle mountains, Oklahoma; Ouachita Mountains, Oklahoma and Arkansas; Ozark Mountains, Oklahoma, Arkansas and Missouri; and northeast Iowa. In the Ozarks, the Ordovician is much more extensively exposed than is the Cambrian. Not only does it cover a much wider area in Missouri, but is found in large outcrops in northern Arkansas, and in several small outcrops in northeast Oklahoma.

Llano uplift, Texas.—In the Llano uplift the Lower Ordovician is represented by the upper Ellenburger limestone. According to faunal studies by Dake and Bridge (1), equivalents of the Gasconade, Roubidoux, Jefferson City and Cotter formations, of the Ozark region are recognized. Younger units of the Ordovician are not present in the area.

Arbuckle and Wichita mountains, Oklahoma.—The Ordovician is represented in the Arbuckle and Wichita mountains by a great thickness of limestone, shale and sandstone, divided into the Arbuckle and Simpson groups, Viola limestone, Fernvale limestone, and Sylvan shale. Decker (2, 3) has described five formations of the Ordovician part of the Arbuckle, some of which were named by Ulrich. They are, in ascending order: McKenzie Hill formation, divided into Chapman Ranch and McMichael limestone members; Strange dolomite; Cool Creek limestone and chert; Kindblade limestone; and West Spring Creek limestone. Ulrich has found Gasconade fossils in the McKenzie Hill formation of the Wichitas and Arbuckles, and considers the Chapman Ranch equivalent to the Van Buren (4). Bases for definite correlation of younger divisions of the Arbuckle are not available, although Bridge (5) makes an approximate correlation of the Cotter with some part of the Kindblade, and the Smithville with the West Spring Creek, on the basis of *Ceratopeas*.

Decker (6) divides the Simpson group into five formations: Joins, Oil Creek, McLish, Tulip Creek, and Bromide. These are well represented in the western (Arbuckle anticline) part of the Arbuckle Moun-



FIG. 3.—Distribution of Ordovician rocks in Mid-Continent region. Solid areas denote outcrops. Stippling indicates areas producing oil and gas from Ordovician rocks. Numbers correspond with areas listed in Chart III.

ORDOVICIAN

	1	2-3	4-5	6-A	6	7
	LLANO UPLIFT	WICHITAS ARBUCKLES	OUACHITAS	OZARKS (OKLAHOMA)	OZARKS (MO.-ARK.)	N. E. IOWA
S		LOWER HUNTON	BLAYLOCK SS.	ST. CLAIR	GIRARDEAU	ALEXANDRIAN
ORDOVICIAN	UPPER ELLENBURGER	SYLVAN SH.	POLK CREEK	?	ORCHARD CR. THEBES	MAQUOKETA
		FERNVALE LS.	---?---	FERNVALE	FERNVALE	
		VIOLA LS.	BIG FORK CHERT		KIMMSWICK	GALENA
		BROMIDE	WOMBLE SH. (STRINGTOWN)	FITE ?		DECORAH
		TULIP CREEK			PLATTIN	PLATTEVILLE FM.
		Mc LISH		TYNER	JOACHIM	?
		OIL CREEK		BURGEN	DUTCHTOWN	ST. PETER
		JOINS			ST. PETER	
		WEST SPRING CR. LS.			BLACK ROCK	
		KINDBLADE LS.	BLAKELY SS.	COTTER ?	SMITHVILLE	
€	LOWER ELLENBURGER	COOL CREEK LS. & CHERT	MAZARN SH.		POWELL	SHAKOPEE
		STRANGE DOL.			COTTER	
		Mc KENZIE HILL FM.	CRYSTAL MT. SS.		JEFFERSON CITY	
		Mc MICHAEL LS. MEMBER			ROUBIDOUX	ONEOTA
		CHAPMAN RANCH LS. MEM			GASCONADE	
			COLLIER SH.		VAN BUREN	
			?		EMINENCE	TREMPEALEAU
		LOWER ARBUCKLE		PRE-CAMBRIAN	POTOSI	

* EXACT EQUIVALENTS NOT KNOWN

CHART III.—Subdivisions, nomenclature, and best available correlations of Ordovician rocks in different areas.

tains, but all are thinner; and the Joins is absent on the east. Contrary to previous statements, Decker now believes that 20-30 feet of Tulip Creek is present in the eastern area (7). Only the uppermost part of the Bromide formation is exposed in the Wichita area, but a considerable thickness of the Simpson group is doubtless present beneath covered areas between outcrops of Viola and Arbuckle limestones. Cram (8) recognized over 1,500 feet of Simpson in cuttings from wells drilled in the general vicinity of Gotebo. Exact correlations of these formations with subdivisions in the Ozark areas have not been established, although the Bromide contains a Black River fauna, and is equivalent to the Plattin of Missouri and Platteville and possibly Decorah of the upper Mississippi Valley.

The Viola limestone consists, rather uniformly, of cherty, dense, limestone, of Trenton age. In the Arbuckle Mountains area it ranges in thickness from about 200 feet to almost 900 feet. It is thickest in the west end of the Arbuckle anticline and in the Criner Hills, and thinnest in the extreme eastern part of the area (9). In the Wichita Mountains, Decker (9) reports 517 feet of Viola, while Cram (8) records 935 feet penetrated by wells in the vicinity. Decker (9) recognized 502 feet of Viola in the vicinity of Atoka, at the west side of the Ouachita area, in rocks formerly classed as the lower part of the Talihina chert, and classed as Bigfork chert by Hendricks, Knechtel, and Bridge (10).

In both the Arbuckles and Wichitas, the Viola is overlain by the coarsely crystalline Fernvale limestone. In the Arbuckles, the Fernvale is overlain by the Sylvan shale, and the two are of Richmond age, hence are at the top of the Ordovician. The Sylvan does not crop out in the Wichita area, but is assigned a thickness of 245 feet in Cram's subsurface section.

Ouachita Mountains, Oklahoma and Arkansas.—In the Ouachita Mountains, the Crystal Mountain sandstone, Mazarn shale, and Blakely sandstone are thought to be partly equivalent to the Ordovician part of the Arbuckle limestone. No fossils have been found in the Crystal Mountain, but graptolites from the Mazarn and Blakely are of Beekmantown age (11, 12), hence these units are correlative with part of the Arbuckle.

Overlying the Blakely sandstone, and including the remainder of the Ordovician rocks of the area, are: Womble or Stringtown shale, Bigfork chert, and Polk Creek shale. They are considered equivalent to the Simpson group, Viola limestone, and Fernvale limestone or Sylvan shale, respectively. The Bigfork and Polk Creek are equivalent to the lower Talihina chert, as originally defined by Taff.

Ozark area, Missouri, Arkansas, and Oklahoma.—A thick and well developed section of the Ordovician is found in the Ozark area, particularly in Missouri, and this may well be considered the standard section for the Ordovician in the Mid-Continent area. This section has been divided as follows: Van Buren formation, Gasconade dolomite, Roubidoux sandstone, Jefferson City dolomite, Cotter dolomite, Powell limestone, Smithville formation, and Black Rock formation, all of Beekmantown age; Everton limestone, St. Peter sandstone, Dutchtown limestone, and Joachim dolomite, of Chazy age; Plattin limestone, of Black River age; Decorah shale and Kimmswick limestone, of Trenton age; and Fernvale limestone and Maquoketa shale (containing the Thebes sandstone and Orchard Creek shale), of Richmond age.

The Jefferson City is the oldest formation exposed in northern Arkansas, but older units have been found in wells, and may represent the Van Buren, Gasconade and Roubidoux. The Smithville and Black Rock are best known in Arkansas, but are present in Missouri (13). The position of the Decorah shale appears to be represented by an hiatus, and the Cason shale, at the top of the Ordovician in Arkansas, is equivalent to the Sylvan of Oklahoma, and the Maquoketa of the upper Mississippi Valley.

In northeast Oklahoma, the section is very much abbreviated, and punctuated by breaks. It is represented by the Cotter dolomite, which rests on pre-Cambrian granite, and is equivalent to part of the upper Arbuckle; Burgen sandstone, which Cram (14) thinks may be equivalent to part of the Oil Creek formation of the Simpson group; Tyler formation (restricted), whose lower portion is thought by Cram (14) to be also lower Simpson, while the upper portion is of Black River age, and equivalent to part of the Bromide formation; the Fite limestone, also related to the Bromide (15) and Fernvale limestone, of Richmond age. From the vicinity of Tahlequah, north to Spavinaw, units from the Fernvale to Cotter were truncated by pre-Chattanooga erosion, so the Chattanooga shale rests on successively older portions of the Ordovician.

Northeast Iowa (16).—The Ordovician section of northeast Iowa is composed of the Oneota dolomite, and Shakopee (Willow River) limestone, equivalent to Missouri units from the Van Buren to Cotter, inclusive; the St. Peter sandstone, with an unconformity at the base; Platteville limestone (Black River); and the so-called Trenton (Galena) group of Trowbridge (16), composed of Decorah shale, Prosser limestone, Stewartville dolomite, and Dubuque formation; and the Maquoketa shale, of Richmond age, which occurs at the top of the

Ordovician. No equivalent of the Fernvale is reported from this area, although according to some interpretations, the Fernvale is represented in the Maquoketa (17).

Ordovician in subsurface.—The Ordovician in subsurface, is of great economic importance, because of its prolific production of petroleum. This is especially true in Oklahoma, where the famous "Wilcox" sand of the Simpson group, is extensively developed; and in Kansas, where the "siliceous lime" of the Arbuckle group, is an important producer. Ordovician production has also been found in several places in Texas, including Cooke County (18) and Young and Callahan counties (19), North Texas; and in Reagan County (20, 21, 22), West Texas.

Ordovician strata of the same facies of rocks as those cropping out in the Llano uplift, have been found in many places in the area north and west of the uplift, though the Ordovician has been removed by pre-Pennsylvanian erosion in the area of the Red River "high" (parts of Denton, Cooke, and Montague counties), in the Panhandle area, and in parts of Foard and Pecos counties (23).

In northeast Texas, several wells have encountered Ordovician and younger rocks, beneath the Cretaceous, that have a lithologic facies wholly unlike that found in areas to the west, and closely resembling the facies found in the Ouachita Mountains of Oklahoma and Arkansas, and in the Marathon area of southwest Texas (24).

In Oklahoma and Kansas, the Ordovician is generally present in the subsurface, except where completely removed by pre-Pennsylvanian erosion, on local "highs." The younger units are missing in northeastern Oklahoma and southeastern Kansas (25, 26), due to pre-Chattanooga truncation, in a manner similar to that described under outcrops in northeast Oklahoma; and in western Kansas, due to pre-Pennsylvanian erosion. The character and distribution of the Ordovician, in the subsurface of Kansas, has recently been described by Koester (27), who states in a recent letter:

In general in Western Kansas, the best oil recoveries are found in the Canadian part of the Arbuckle, where beds of Simpson age intervene between the Arbuckle and the Pennsylvanian (28).

The "Wilcox" sand is economically the most important unit of the Ordovician, because of the high yields per acre of petroleum that have been obtained from it. The "Wilcox" belongs to the Simpson group, but it cannot be certainly identified with subdivisions of that group. As a matter of fact, it is probable that the sands called "Wilcox" in different producing areas, are actually of somewhat different ages. Other sands of the Simpson commonly produce in the same field as the

"Wilcox," and both the Viola and Fernvale, as well as the Arbuckle, yield important production.

The Viola limestone thins within a short distance, in the subsurface, northward from the vicinity of the Arbuckle Mountains, and is absent in the Greater Seminole area, and on the north. The Fernvale limestone, commonly called "Viola," is an extremely persistent unit, and an excellent marker and datum for subsurface structure mapping. Beneath the Fernvale, at the top of the Simpson, is a "dense lime," that is probably the same as the Fite (14, 15).

A small amount of oil has been produced recently from limestone of Viola age, in the Falls City field of southeastern Nebraska.

SILURIAN AND DEVONIAN

The Silurian and Devonian rocks in the Mid-Continent region are much more restricted, both in area of outcrop and in representation, than the Ordovician. Where present, the sequence is incomplete in comparison with the standard New York section, and total thicknesses are comparatively small. The most complete section is found in eastern Missouri.

No Silurian or Devonian is exposed in the Llano uplift, Texas, or in the Wichita Mountains, Oklahoma.

Arbuckle Mountains, Oklahoma.—In the Arbuckle Mountains, the Silurian is represented by the Chimneyhill limestone and Henryhouse shale, of middle Silurian age (Niagaran, and upper Medina) (1); and the Devonian, by the Haragan shale, Bois d'Arc limestone, and Frisco limestone, of Lower Devonian age (Helderberg to Oriskany). Together these formations are known as the Hunton limestone. Most of the units are separated by marked erosional unconformity, resulting in great variability of thickness, and locally in the complete absence of whole formations. A detailed study of the Hunton group, and further subdivision has been made recently by Maxwell (2).

Ouachita Mountains, Oklahoma and Arkansas.—In the Ouachita Mountains, rocks classified as Blaylock sandstone and Missouri Mountain slate, are referred to the Silurian (3). The Blaylock sandstone is absent in the Oklahoma part of the Ouachitas, except in McCurtain County, and therefore is not represented in Taff's (4) Talihina chert. The Missouri Mountain slate, however, is of widespread occurrence, and equivalent to part of the Talihina. Fossils identified by Ulrich (3) from the Blaylock sandstone, led him to assign the Blaylock to Lower Silurian, but no fossils have been found in the Missouri Mountain. The position of the latter between the Blaylock (early Silurian), and the Arkansas novaculite (the lower part of which is



FIG. 4.—Distribution of Silurian and Devonian rocks in Mid-Continent region. Solid areas denote outcrops. Stippling indicates areas producing oil and gas from Silurian and Devonian rocks. Circles indicate drill holes that contribute subsurface information. Numbers correspond with areas listed in Chart IV.

SILURIAN - DEVONIAN

	1	2-3	4	4-A	5	6
	ARBUCKLES	OUACHITAS (OKLA. - ARK.)	OZARKS N. E. OKLAHOMA	OZARKS (ARKANSAS)	MISSOURI	N. E. IOWA
	WOODFORD SH.	UPPER ARK. NOVACULITE	SYLAMORE SS.	SYLAMORE SS.	KINDERHOOK	KINDERHOOK
DEVONIAN	FRISCO L.S. BOIS D'ARC L.S. HARAGAN SH.	LOWER ARKANSAS NOVACULITE (TALIHINA)	SALLISAW SS. FRISCO L.S.	CLIFTY L.S. PENTERS CHERT	SNYDER CREEK CALLAWAY - ST. LAURENT BEAUVAIS GRAND TOWER LITTLE SALINE CLEAR CREEK BAILEY	SHEFFIELD LIME CREEK SHELL ROCK CEDAR VALLEY INDEPENDENCE WAPSIPINICON
SILURIAN	HENRYHOUSE CHIMNEY HILL	MISSOURI MT. SLATE BLAYLOCK SANDSTONE	UPPER ST. CLAIR LOWER ST. CLAIR	LAFFERTY ST. CLAIR BRASSFIELD	BAINBRIDGE REPRESENTED BRASSFIELD EDGEWOOD GIRARDEAU	GOWER HOPKINTON WAUCOMA
	ORDOVICIAN	ORDOVICIAN	?	ORDOVICIAN	ORDOVICIAN	ORDOVICIAN

CHART IV.—Subdivisions, nomenclature, and best available correlations of Silurian and Devonian rocks in different areas.

Middle Devonian), indicates the Missouri Mountain slate is Silurian or Devonian (5, 6).

The succeeding Arkansas novaculite is equivalent to part of Taff's Talihina chert, and the lower portion is considered Devonian (3). The upper part is equivalent to the Woodford chert and Chattanooga shale which the United States Geological Survey considers Devonian (?), but which most Oklahoma geologists regard as lower Mississippian (Kinderhook).

With the possible exception of the Arkansas novaculite, these rocks in common with the underlying Cambrian and Ordovician of the area, have lithologic facies quite distinct from their correlatives in adjacent areas.

In Sec. 5, T. 2 N., R. 15 E., Pittsburg County, Oklahoma, in the Ti Valley area of the northern Ouachita Mountains, is a small exposure of fossiliferous chert and limestone, of Onondaga age, known as the Pinetop chert. The unit is about 50 feet thick (7). Lithologically, this formation is related to Devonian rocks of the Arbuckle and Ozark areas, rather than the Ouachitas. It may be approximately equivalent to the Sallisaw sandstone of the Oklahoma Ozarks, and the Penters chert of the Arkansas Ozarks.

Ozark area, Arkansas and Oklahoma.—Silurian and Devonian rocks are found in several small exposures, within a small area in southeastern Cherokee, southwestern Adair, and northern Sequoyah counties, near Marble City, Oklahoma. The Silurian is represented by the St. Clair "marble," equivalent to the Chimneyhill limestone. Thicknesses up to 100 feet have been recorded, with the base not exposed anywhere in the area (8).

The Devonian is thinly represented by the Frisco limestone and the Sallisaw sandstone, of late Lower, and early Middle Devonian, respectively. Outcrops of these formations are much more restricted in area than the underlying St. Clair, due to pre-Chattanooga planation (8).

In northern Arkansas (9), the Silurian is represented by the Brassfield limestone (lower St. Clair), 5 feet thick, the St. Clair limestone (restricted), 100 feet thick, and the Lafferty limestone (10), 85 feet thick in its only known exposure.

Devonian rocks consist of the Penters chert and Clifty limestone, both of very limited geographic distribution. The Penters chert reaches a maximum thickness of 90 feet, and has been found in but two small areas in Independence County, Arkansas, where it rests unconformably on the St. Clair (10). It has yielded fossils, and its age has been determined on stratigraphic relationships and lithology. The Clifty limestone is exposed in only one place, in southeastern Benton

County, Arkansas, where it ranges from 2 to 4 feet thick. The contained fossils indicate it to be of Middle Devonian (Hamilton) age (11).

Missouri.—Rocks of Silurian age are exposed in Cape Girardeau and Perry counties, southeastern Missouri, and in Pike and Lincoln counties, northeastern Missouri (12). The section in southeastern Missouri consists of the Girardeau, Edgewood, and Brassfield formations, of Medina age; and unnamed beds of Osgood and St. Clair affinities, and the Bainbridge formation, of Niagaran age (13).

The Devonian of the same area contains the following: Bailey limestone (Helderberg), Little Saline limestone (Oriskany), Grand Tower limestone (Onondaga), Beauvais sandstone (Marcellus), and St. Laurent limestone (Hamilton) (14).

In northeastern Missouri, the Lower Silurian Girardeau formation is absent, and the Silurian includes the Edgewood formation and the Sexton Creek (Brassfield) limestone (15, 16).

In the same area, the Devonian is much restricted. Equivalents of the Bailey and Little Saline (Helderberg and Oriskany) are absent, while the Onondaga is represented by the Cooper and Mineola limestones, approximately equivalent to each other, and to the Grand Tower formation. The Upper Devonian is represented by the Callaway limestone, approximately equivalent to the St. Laurent; and the Snyder Creek shale (12, 17).

Iowa.—Silurian rocks are exposed in northeastern Iowa, in the area between Davenport and West Union, and the Devonian, in a wide band, parallel with the Silurian, extending from Muscatine, northward through Mason City, to the Minnesota line.

The Silurian section contains representatives of most of the Missouri units, except the Girardeau. The formations are Waucoma (Alexandrian), Hopkinton, and Gower (Niagaran). Only the Upper Devonian is present, represented by the Wapsipinicon formation; the thin Independence shale; Cedar Valley limestone, which has a greater surface extent than any other single Devonian formation in the state; Shellrock formation; Lime Creek formation and Sheffield formation. Another unit, the State Quarry limestone, of local distribution in Johnson County, rests unconformably on the Cedar Valley, but its relationship to the Shellrock, Lime Creek, and Sheffield, has not been established (18).

Silurian and Devonian in subsurface.—Considerable oil is produced from Silurian and Devonian rocks in the Mid-Continent area, particularly in Oklahoma and Kansas, where the producing formation consists of limestone, which is called "Hunton," and represents both the Silurian and Devonian.

Numerous wells drilled in central Texas into Ordovician formations, indicate the absence of Silurian and Devonian rocks. Harlton and Lowman report Devonian in deep wells in the Big Lake field, Reagan County, but "these reports have not been satisfactorily confirmed" (19). Rocks of the Ouachita facies, possibly of Silurian and Devonian age, have been found in wells drilled in Bell, Falls, Hays, and Williamson counties (19).

The "Hunton" is probably present in subsurface in the greater part of central and western Oklahoma, except in local "highs" along the Central Oklahoma uplift. In the vicinity of the Wichita Mountains, Cram (20) reports 605 feet of "Hunton," composed mostly of limestone, with some magnesian limestone, and in the lower part, chert and oölites.

In part of the Greater Seminole district, pre-Chattanooga erosion removed all the "Hunton," and Woodford shale is found resting on Ordovician rocks. The "Hunton" is an important producing horizon in the Greater Seminole district, Seminole and Pottawatomie counties, and in other fields located in Okfuskee, Pontotoc, and Lincoln counties, Oklahoma.

It produces oil in several fields in Sedgwick, McPherson, Harvey, Reno, and Rice counties, Central Kansas, and is present in the Salina Basin of north-central Kansas, and the Forest City basin of northeast Kansas, northwest Missouri, southeast Nebraska, and southwest Iowa. Silurian rocks have been recognized in wells in most of Nebraska except in the vicinity of the Chadron anticline in the northwestern part of the state, and the Cambridge anticline, south-central Nebraska (21). The Devonian appears to be present only in eastern Nebraska, while both Silurian and Devonian are probably present in subsurface in most of Iowa and northern and western Missouri.

The first commercial oil field in the Forest City basin, and in the state of Nebraska, was opened in 1939, near Falls City, producing from the "Hunton."

MISSISSIPPIAN AND PENNSYLVANIAN

The problem of the proper classification of Mississippian and Pennsylvanian rocks in North America is now being actively debated by stratigraphers, some holding that they should have series rank, under the Carboniferous system, others that they are entitled to independent, systemic rank. The former base their argument on the advisability of conforming with European usage, the latter on the more natural and useful division of the rocks in North America.

The question is being considered by the sub-committee on Car-

boniferous of the Association's geologic names and correlations committee, of which the writer is a member, but no final decision has yet been reached by the committee.

A similar sub-committee on the Permian, in 1939, decided that Permian should have systemic rank, and recommended a four-fold division into series.

For the purpose of this paper, the writer, entirely on his own responsibility, is assigning systemic rank to the Mississippian and Pennsylvanian, for the following reasons: 1, general usage among Mid-Continent geologists; 2, the natural division into two systems of the rocks exposed in the Mid-Continent region; 3, the relative order of magnitude, as measured in thickness, of Mississippian, Pennsylvanian, and Permian; 4, the comparable magnitude of the major subdivisions of Mississippian, Pennsylvanian, and Permian.

In amplification of this latter, if Wolfcamp, Leonard, Guadalupe, and Ochoa are to be of series rank, then it would seem that Morrow, Des Moines, Missouri, and Virgil, subdivisions of the Pennsylvanian, and Kinderhook, Osage, Meramec, and Chester, subdivisions of the Mississippian, are entitled to equal and coördinate rank—hence, the Mississippian and Pennsylvanian should be coördinate with Permian.

MISSISSIPPIAN

The Mississippian is represented throughout most of the Mid-Continent region, but is best developed in the Ozark area of Oklahoma, Arkansas, and Missouri, and in Iowa. It does not crop out in the Wichita Mountains, Oklahoma, and the section is very thin and incomplete, in the Llano uplift, Texas.

Throughout the Mid-Continent area, from south-central Oklahoma, northward, the basal Mississippian unit is black, fissile shale, of varying thickness, called the Chattanooga, and referred by most Mid-Continent geologists to the Kinderhook, although the United States Geological Survey classifies it as Devonian (?).

In most of the northern Ozark area and northward into Iowa, the succeeding Mississippian section is characterized by the abundance of conspicuous limestones, whereas on the south flank of the Ozarks, in Oklahoma and Arkansas, many of these limestones grade into dark shale. In the vicinity of the Arbuckle Mountains, Oklahoma, rocks of Mississippian age are dark shale, chert, and some limestone. The differences in faunas, associated with the change in facies of lithology, makes exact correlations of these rocks with their equivalents in other areas, rather difficult.

Llano uplift, Texas (1).—Mississippian rocks crop out locally in the



FIG. 5.—Distribution of Mississippian rocks in Mid-Continent region.
Numbers correspond with areas listed in Chart V.

MISSISSIPPIAN

SERIES	1	2	3	4	5	6	7
	LLANO UPLIFT	ARBUCKLES	OUACHITAS (OKLA.)	OUACHITAS (ARK.)	OZARKS (S.W.)	OZARKS (N.E.)	IOWA
	MORROW	SPRINGER FM.	STANLEY SH.	HOT SPRINGS SS.	MORROW	DES MOINES	DES MOINES
CHESTER	?	?			PITKIN L.S. FAYETTEVILLE SH. BATESVILLE SS.	CHESTER	CHESTER
MERAMEC	?	?			MOOREFIELD ?	STE. GENEVIEVE ST. LOUIS SPERGEN WARSAW	MERAMEC
OSAGE	CHapel L.S. (BOONE AGE)	WELDEN L.S.			BOONE FM. ST. JOE L.S.	KEOKUK BURLINGTON FERN GLEN	OSAGE
KINDERHOOK		SYCAMORE L.S. PRE-WELDEN SH. WOODFORD SH.	UPPER TALIHINA CHERT	UPPER ARKANSAS NOVACULITE	CHATTANOOGA SH. SYLAMORE SS.	CHOUTEAU HANNIBAL GLEN PARK LOUISIANA CHATTANOOGA	KINDERHOOK
	ORDOVICIAN	FRISCO L.S.	LOWER TALIHINA	LOWER ARKANSAS NOVACULITE	DEVONIAN TO ORDOVICIAN	DEVONIAN TO ORDOVICIAN	UPPER DEVONIAN

CHART V.—Subdivisions, nomenclature, and best available correlations of Mississippian rocks in different areas.

Llano uplift, and are thinly represented by the Chappel limestone, of Boone (Osage) age, and the lower Barnett shale, of Meramec age (2). The upper part of the Barnett contains Pennsylvanian (Springer) fossils (3). The Chappel formation is known in only a few, small exposures on the north and west sides of the uplift, and attains a thickness of only a few feet. It rests disconformably on the Ellenburger limestone (Ordovician), and is disconformably overlain by the Barnett shale.

The Barnett consists mainly of dark, bituminous shale, with a few feet of limestone at the top. It is exposed in a narrow belt around the north end of the Llano uplift, and is in places wanting. Its outcrop thickness ranges from a few feet to 30 or 50 feet. It rests unconformably on either the Chappel or Ellenburger, and is disconformably overlain by the Marble Falls limestone (Pennsylvanian). This contact is marked by the presence of glauconite and phosphate.

Arbuckle Mountains, Oklahoma.—The Hunton limestone (Devonian) is succeeded by the Woodford shale, which consists of black, fissile, bituminous shale, locally containing large amounts of chert. It has an average thickness of 625 feet (4). The Woodford is correlated with the Chattanooga shale of the northern areas.

In the western (Arbuckle anticline) part of the area, the Woodford is succeeded by the Sycamore limestone, which decreases in thickness from 750 feet at the west end of the Arbuckle anticline (5), to 50 feet near Washita River (6). The Sycamore is present on only the western and southern margins of the eastern portion of the Arbuckle Mountains area (Hunton-Tishomingo uplift) (7), where it thins and disappears northeastward a few miles south of Sulphur.

On the eastern margin of the Hunton-Tishomingo uplift, particularly, on the Lawrence uplift part, a clay shale, about 1 foot thick, and the overlying Welden limestone, 2 feet thick, intervene between the Woodford and Caney formations (5).

Considerable confusion exists as to the relative age of the Sycamore and Welden, since the two have not been found in the same exposures. Because of its position, Morgan (8) mapped as Sycamore the limestone later called Welden.

Subsurface stratigraphers, working with cuttings of wells drilled in the vicinity of the Arbuckle Mountains area have recognized a "grayish-white, finely crystalline limestone, 5 to 10 feet thick," which they consider to be Welden, overlying the Woodford (9). Above the Welden is a "brownish-to-grayish, highly calcareous, gritty shale," which is called "Mayes," and has been considered as "equivalent to the Sycamore limestone."

The Sycamore has been determined to belong to the Kinderhook,

probably representing the Chouteau formation (8, 10, 11). On the basis of megafossils collected from the Welden in 1929, Girty (quoted by Cooper) (5) correlated this limestone with the Chappel formation (of Boone age), of Texas, thus making it considerably younger than the Sycamore. In the thin shale between the Woodford and Welden, Cooper (5) found a micro-fauna similar to that of the Bushburg-Hannibal formation of the Kinderhook, which makes this shale slightly older than Sycamore.

In view of this paleontological evidence, it appears probable that the "Mayes" of the subsurface is much younger than Sycamore, is probably represented on the outcrop by calcareous beds in the lower part of the Caney shale, and may be of Meramec age, equivalent to part of the Moorefield shale.

Overlying the Sycamore and Welden, throughout the Arbuckle area, is the Caney shale, consisting of black, bituminous shale, with a zone of large limestone concretions, and other calcareous beds in the lower part. The upper part of the Caney, as originally described by Taff (12), has yielded fossils of Pennsylvanian age (8, 13), and is now referred to the Springer formation (14). The Mississippian-Pennsylvanian contact falls within a thick shale, and is difficult to recognize in the field. In the few existing exposures, division can be made on the basis of slight differences in lithology and fossils.

The unusual character, and the fossils of the Caney shale, make its exact correlation with the type Mississippian section rather difficult. It is generally believed to be equivalent to the Meramec, and at least part of the Chester groups.

Ouachita Mountains, Oklahoma and Arkansas.—The upper part of the Arkansas novaculite and Talihina chert are considered to be equivalent to the Woodford shale, because of lithology and fossils, and are therefore referred to the Kinderhook. In Arkansas, the Arkansas novaculite is overlain by the Hot Springs sandstone, which is succeeded by the Stanley shale. In Oklahoma, the Stanley shale directly succeeds the Talihina chert.

Since the Hot Springs and Stanley are now regarded as Pennsylvanian (14, 15, 16), it follows that only the lowermost Mississippian is represented in this area.

Southwestern Ozarks, Oklahoma and Arkansas.—Lithologically, the Mississippian section of the southwestern Ozarks, in general, represents a facies intermediate between the clastic deposits of the Arbuckle area, and the dominantly limestone section of the Mississippi valley. At the base is found the black, fissile, bituminous Chattanooga shale (Kinderhook), which ranges from 26 to 90 feet thick in Oklahoma (4),

and from a few inches to 85 feet, with an average of 30 feet, in Arkansas (17).

At the base of the Chattanooga is the Sylamore sandstone, which is very irregular in thickness, character, and distribution. It is composed of rather coarse, rounded grains of sand, and may contain considerable iron and pebbles of phosphate and shale (18). In some localities in Oklahoma the basal beds are calcareous, and in Arkansas, the formation is generally either calcareous or conglomeratic (17). In Oklahoma, it averages 5.5 feet thick, but near Marble City, attains a thickness of 30 feet. In Arkansas, it is generally 2-5 feet thick, and reaches its maximum of 75 feet near Springdale.

The Sylamore, and in its absence, the basal bed of the overlying black shale, rest variously on all formations from Sallisaw sandstone (Middle Devonian) to Cotter (Ordovician). Cram (18) has demonstrated a progressive, northward planation of these older rocks, by the Chattanooga, along the west edge of the Ozarks, in Oklahoma.

Overlying the Chattanooga is the Boone formation, 100-400 feet thick, which covers most of the surface of the western Ozarks. It is a massive series of limestone and chert, which materials vary in amount, both laterally and vertically. At the base is the St. Joe member, which is free from chert, but varies from coarsely crystalline, crinoidal limestone, to even-bedded, fine-grained limestone, earthy limestone, or dark gray and green shales with thin lenses of limestone (18). The thickness ranges from 5 to 40 feet in Oklahoma, and from a feather edge to 100 feet, with an average of 25 or 30 feet, in Arkansas.

The St. Joe is correlated with the Fern Glen, of the standard section, and Laudon (19) divides the cherty Boone into the Reeds Springs and Keokuk formations. He states that the Reeds Springs has no correlatives outside the type area of southwest Missouri, northeast Oklahoma, and northwest Arkansas, though Moore (20) (cited by Laudon) recognizes beds of Reeds Springs age in the Fern Glen sections of southeast Missouri. Laudon states further that "the Burlington formation, so excellently developed in northeastern Arkansas and southeastern Missouri is not present in the Oklahoma sections."

Snider (21), Taff (22), and Moore (23) (all cited by Cram) report lower Burlington and Warsaw fossils from the Boone, and Purdue and Miser (24) (cited by Cram and Croneis) consider that beds above the Short Creek oölite (upper Boone) are early Warsaw. Cram (18) summarizes as follows (p. 558).

The continuity of the Boone in Oklahoma with that of Arkansas and southwestern Missouri coupled with the evidence presented above indicates that the Boone ranges in age from Fern Glen to lower Warsaw. . . .

In different parts of the area, the Boone is succeeded by the Moorefield shale or the next younger Batesville sandstone. At the base of the Moorefield shale, in its type area near Batesville, is a thin, fossiliferous, calcareous zone, that has been called the "Spring Creek" limestone. Girty described "... a series of fine-grained impure and cherty limestones ..." (25), from the vicinity of Batesville, that had been classed as part of the Boone, but which contain a fauna unlike the typical Boone and almost identical with that of the overlying "Spring Creek." In western Cherokee, eastern Muskogee, and southern Mayes counties, Oklahoma, is black, calcareous micaceous, slaty shale, in many places plentifully fossiliferous, with a fauna that is very similar to that of the "Spring Creek." This calcareous unit is the lower part of Snider's Mayes formation (21).

In Arkansas, the "Spring Creek" is overlain by the main part of the Moorefield, a black shale ranging up to 275 feet thick, thinning westward from the type area, and disappearing in Searcy County. This upper part of the Moorefield is absent in Oklahoma. In Arkansas, it contains a fauna similar to that found in the Caney shale of the Arbuckle area, Oklahoma.

The Moorefield shale is overlain by the Batesville sandstone, which crops out along the base of the slopes and isolated hills north of the Boston Mountains escarpment, in northwestern Arkansas. On the northwest, it is thin or absent. Snider (21) reported a Batesville fauna in the area north of Chouteau, Mayes County, Oklahoma, from part of his Mayes formation. He states that the beds containing the Moorefield ("Spring Creek") fauna die out, and those containing the Batesville fauna come in at this point, and the latter thicken toward the north. In parts of northern Arkansas, the Hindsville limestone member is present in the basal part of the Batesville sandstone.

Above the Batesville sandstone is the Fayetteville formation, generally black, fissile, carbonaceous shale. Throughout the Arkansas part of its outcrop, there is a prominent sandstone, called Wedington, near the top, but this unit extends only a few miles into Oklahoma. Some limestone occurs above the Wedington, while fossiliferous limestone and sideritic concretions are found near the base of the formation. Such limestones, found at the base of the Fayetteville in Oklahoma were included by Snider (21) in his Mayes formation. In Mayes and Muskogee counties, other prominent limestones are found near the top of the formation.

The Fayetteville conformably overlies the Batesville sandstone, except where that unit is absent, in which areas, it rests disconformably on the Boone, or some part of the Moorefield. The thickness

ranges from 10 to 400 feet in Arkansas, decreasing toward the north and northwest. The thickness in Oklahoma ranges from 20 to 160 feet, decreasing toward the southwest.

Overlying the Fayetteville, and generally conformable with it, is the Pitkin limestone, the uppermost Mississippian formation of the area. It ranges in thickness from a few feet to 100 feet, with an average of about 40 or 50 feet. Locally it is thin or absent, owing to pre-Pennsylvanian erosion.

The Pitkin is succeeded by rocks of the Morrow group (basal Pennsylvanian), or in areas of extensive post-Morrow erosion, by younger Pennsylvanian strata. The basal Morrow is the Hale formation, which in Arkansas is a calcareous sandstone. [In Oklahoma, especially near Muskogee, the Hale is so calcareous as to be more properly called limestone, and its separation from the Pitkin is difficult. The contact is usually marked by a thin layer of conglomerate, and a zone of phosphatic concretions. Carl Moore (26) has recently found insoluble residues to be reliable criteria for separating the two formations.

As already indicated, the Chattanooga is classed as Kinderhook and the St. Joe and overlying Boone, as Osage, possibly extending into the Meramec. The Moorefield is considered to be Meramec, while the Batesville, Fayetteville, and Pitkin, are referred to the Chester. The Caney shale of the Arbuckle area is correlated with at least the shale part of the Moorefield, and Cooper (5) suggests that perhaps the Welden limestone is equivalent to the "Spring Creek" limestone, at the base of the Moorefield. Many geologists believe that part or all of the Fayetteville shale is represented in the Caney (18).

As stated above, the Mississippian rocks of this area, particularly those representing the Meramec and Chester groups, show lithologic and faunal facies different from those of equivalent rocks in the type region, making exact correlations extremely difficult. Even the Boone differs considerably from its northeastern equivalents. In the Mississippi valley, the section is characterized by limestone, here by black shales and cherts, with limestones less conspicuous. Cram (18, p. 567) calls attention to a similar southward gradation of Mississippian rocks in Alabama, Tennessee, Kentucky, Indiana and Illinois.

Missouri.—Mississippian outcrops in Missouri flank the west and north sides of the Ozark uplift, and extend northeastward, along the Mississippi valley, into Iowa. Mississippian rocks are also present in the lower Mississippi valley, in Perry and Ste. Genevieve counties.

The Mississippian formations of Missouri consist mainly of limestone, but include also sandstone and shale. The limestone is mostly coarse-grained and highly crystalline, and it is commonly marked by a profusion of well pre-

served fossils. In general the limestone is very cherty. Shale formations are thin, clayey and sandy and are generally blue, greenish or black. Sandstone is almost negligible. . . .

The average thickness of the Mississippian rocks in Missouri is about 500 feet, but on account of original irregularities of deposition and the uneven manner in which pre-Pennsylvanian erosion removed parts of the Mississippian formations, the thickness varies notably from the average. In general the depositional record appears to have been least complete in the north and to the west, the later Mississippian formations being thin or absent in these portions of the state. The total thickness increases southward, and along the Mississippi River south of St. Louis the rocks of this system are at least 1,000 feet thick (23).

These rocks are classified into the following groups: Kinderhook, Osage, Meramec, and Chester.

The Kinderhook is composed of the Chattanooga, Louisiana, Glen Park, Hannibal and Chouteau formations. In the Joplin district, southwestern Missouri, is found a thin section of Kinderhook, overlain by the Boone (Osage).

The Sylamore sandstone, at the base of the Chattanooga extends only to central Missouri, where it is overlain by the Chouteau limestone, the intermediate units being absent. In northeastern Missouri, the Chattanooga is represented, where present, by the Saverton and Grassy Creek shale, followed by the Louisiana, Hannibal, and Chouteau formations, the Glen Park being absent. In southeastern Missouri, the Glen Park and the Bushberg member of the Hannibal, are the only representatives of the Kinderhook.

The Osage group is well developed in the central, northeastern, and southeastern parts of the state, and contains the Fern Glen, Burlington, and Keokuk formations. In the Joplin district, the Osage, and lower Meramec (Warsaw formation) are represented by the Boone chert. This formation is of considerable economic importance in this area and adjacent parts of Kansas and Oklahoma, for it yields the zinc and lead ore of the famous Tri-State mining district. It is also interesting to note that numerous seeps of "tar"—heavy asphaltic oil—are encountered in some of the mines, from the Boone (27).

The Meramec group, chiefly limestone, attains its greatest development along the Mississippi River from Ste. Genevieve County north into St. Louis and St. Charles counties, and from Marion County north into Iowa. The Meramec group contains the Warsaw, Spergen, St. Louis, and Ste. Genevieve limestones.

The uppermost group of Mississippian rocks (Chester), occupies a small area in Perry and Ste. Genevieve counties, and consists of limestone, sandstone, and shale. Patches of Chester (Carterville forma-

tion), chiefly preserved in old sink holes, are found near Joplin, in Jasper County.

Iowa.—The Mississippian formations constitute bed rock in a diagonal belt 20–60 miles wide, extending from the southeast corner of Iowa, northwest through the central and north-central parts of the state, into Minnesota. The Kinderhook, Osage and Meramec groups are represented, but rocks of Chester age are absent (28).

The stratigraphic relations of the Mississippian formations among themselves are somewhat complex. . . . The Burlington, Keokuk, Warsaw and Spergen formations are confined to the southeastern part of the state. The St. Louis limestone overlaps these deposits and rests directly upon the Kinderhook in north-central Iowa. The Ste. Genevieve deposits extend to this section of the state also. In the Ft. Dodge area they are found above the St. Louis rocks. . . . (28).

Laudon (29) states that “. . . the Chester series is represented by only a single formation.”

Laudon (29) divides the Kinderhook into Maple Mill, including the Sweetland Creek (Chattanooga); English River (Hannibal); and Hampton (Chouteau). These formations contain different members in southeastern and north-central Iowa.

The Osage group contains the Burlington and Keokuk formations; and the Meramec contains the Warsaw, Spergen, St. Louis and Ste. Genevieve formations. Laudon (29) refers the youngest Mississippian formation (Pella) to the Chester, while Van Tuyl (28) considers it part of the Ste. Genevieve.

In southeastern Iowa and in Webster County the border of the main body of Pennsylvanian strata rests on the St. Louis and Pella formations but occasional outliers of the “Coal Measures” to the northeast rest on older beds ranging down to the Kinderhook. In central and north-central Iowa the Pennsylvanian beds are in contact with the Kinderhook almost everywhere along the boundary of the two systems except in Webster County as noted above, and in western Humboldt and western Kossuth counties, where Cretaceous sediments succeed the Kinderhook. (28).

Mississippian in subsurface.—The Mississippian in subsurface is of great economic importance because of the large number and widespread distribution of fields in Kansas and Oklahoma that produce oil and gas from the “Mississippi lime,” and from the Misener sand (Sylamore).

In Texas,

. . . a Mississippian limestone has been more or less definitely recognized underground over a large area north, west and southwest of the Llano uplift. Among the counties in which it is recognized are Callahan, Coleman, Eastland, Edwards, Shackelford, Throckmorton, and Young. . . . Limestones of this age may also be present in some of the deep wells in Reagan County although this inference at present lacks confirmation (1).

This limestone is thought to be equivalent to the Chappel (Osage), and its subsurface thickness, where present, in the area north and west of the Llano uplift ranges from a thin stratum to 150 feet.

The overlying Barnett shale (Chester) is very generally recognized in wells, underlying the Pennsylvanian, northward from the Llano uplift to Young County. Westward it is less well known although it is apparently present in Taylor County. South of the Llano uplift, the Barnett is definitely recognized in only one well, in Kendall County.

Mississippian rocks are found beneath the Pennsylvanian over most of Oklahoma where drilling has been sufficiently deep. Cram (30) reports Chattanooga (Woodford) and Caney from the north side of the Wichita Mountains, and Chattanooga black shale and overlying "Mississippi lime" are known in most parts of the state, the former resting on rocks ranging in age from Hunton (Silurian and Devonian) to Arbuckle (Ordovician). The pre-Chattanooga planation described on the outcrop by Cram (18) has its counterpart in subsurface, as shown by White (31) and McClellan (32), not only in Oklahoma, but also in Kansas. Buchanan (11) has shown that the Chattanooga is locally absent beneath an area in Osage County, Oklahoma, where the "Mississippi lime" rests on Ordovician.

Kinderhook shale (at least in part Chattanooga), is present beneath most of Kansas, except on the nucleus of the Central Kansas uplift. This shale is light gray to black, and ranges up to 60 feet thick (33).

The Misener sand, equivalent to the Sylamore, at the base of the Chattanooga shale, occurs in local patches over much of the producing areas of Oklahoma and Kansas, and produces considerable oil. A small amount of oil production has been found recently in the Misener sand in the Falls City field of southeastern Nebraska.

In Oklahoma, a perplexing problem is presented by the widespread "Mississippi lime." In northeast Oklahoma and Kansas, this is a white, cherty limestone, similar to the Boone of the outcrop, with which it has been correlated. It occupies the position between the Chattanooga (Woodford) and the base of the Pennsylvanian. In parts of central Oklahoma, this same interval includes a black, gritty, argillaceous limestone, called "Mayes," and elsewhere, a black shale occurs above this limestone, and below the Pennsylvanian.

Some subsurface stratigraphers consider this black limestone to be equivalent to Snider's (21) Mayes formation, hence probably Meramec in age, while others regard it as a depositional variant of the Boone, hence Osage in age. The conflicting opinions, and observations upon which they are based, are summarized by Cram (18). The shale above the black limestone is probably Caney.



FIG. 6.—Distribution of Pennsylvanian rocks in Mid-Continent region. Solid areas and arrows denote outcrops of Morrow series in Llano uplift, Arbuckle Mountains, and Ozark Mountains facies. Cross-hatching denotes Morrow outcrops in Ouachita facies. Numbers correspond with areas listed in Chart VI. Arrow in area 3 indicates outcrop of Wapanucka limestone. Arrows in area 5 indicate limits of Morrow outcrops in Ozarks.

PENNSYLVANIAN

SERIES	1	2	3	4	5	6	
	NORTH TEXAS	ARDMORE BASIN	CENTRAL OKLAHOMA	OUACHITA MTS. ARKANSAS VALLEY NORTH OKLAHOMA	OZARKS KANSAS NEBRASKA	MISSOURI	IOWA
	(PUEBLO GROUP)	CLEAR FORK - WICHITA	(STRATFORD SHALE)	(BELOW FORAKER LS.)	(ADMIRE GROUP)	INDIAN CAVE SS	?
VIRGIL	CISCO SERIES	VANOSS FM.	VANOSS FM.	(GRAYHORSE LS.) WABAUNSEE FM. (BUCK CREEK FM.)	(BROWNVILLE LS.) WABAUNSEE GP.	WABAUNSEE	
			ADA FM.	PAWHUSKA FM. ELGIN SS. NELAGONEY FM.	SHAWNEE GP.	SHAWNEE	VIRGIL
			VAMOOSA CONG.		DOUGLAS GP.	DOUGLAS	
MISSOURI	CANYON SERIES			OCHELATA GP.	PEDEE GP.	PEDEE	
		HOXBAR "FM"	OCHELATA BELLE CITY L.S. FRANCIS FM. SEMINOLE SS.	SHATOOK GP.	LANSING GP.	LANSING	
					KANSAS CITY GP.	KANSAS CITY	MISSOURI
DES MOINES	STRAWN "SERIES"	DEESE FM.	HOLDENVILLE - WETUMKA	LENAPAH - FT. SCOTT	MARMATON GP.	PLEASANTON	
		BIG BRANCH FM.	CALVIN - THURMAN BOGGY SH. SAVANNA SS. MC ALESTER SH. HARTSHORNE SS. ATOKA FM.	CALVIN(?) - THURMAN(?) BOGGY SH. SAVANNA SS. MC ALESTER SH. HARTSHORNE SS. ATOKA FM.	CHEROKEE SH.	CHEROKEE	DES MOINES
		LESTER L.S. U. DORNICK HILLS FM. BOSTWICK CONG.					
MORROW	MARBLE FALLS U. BARNETT SH. L. BARNETT SH.	L. DORNICK HILLS FM. SPRINGER FM.	WAPANUCKA FM. SPRINGER FM.	JOHNS VALLEY BOULDER-BEARING SH. JACKFORK SS. STANLEY SH. HOT SPRINGS SS.	BLOYD HALE		
	L. BARNETT SH.	CANEY SH.	CANEY SH.	ARKANSAS NOVACULITE	CHESTER- BOONE	CHESTER	

CHART VI.—Subdivisions, nomenclature, and best available correlations of Pennsylvanian rocks in different areas.

In northwest Oklahoma and southwest Kansas, a considerable thickness of Meramec (Ste. Genevieve) rocks have been found within recent years (34). They are mostly limestone and shale, and are much thicker than Meramec beds exposed on the west flank of the Ozarks. Some oil production is found in this series, in Scott County, Kansas.

A detailed study of the Mississippian rocks in the subsurface of Kansas has been made by Wallace Lee, as a coöperative project of the United States Geological Survey, and the Kansas Geological Survey. Some of the results, showing distribution and thickness in eastern Kansas, and the relation of thickness to oil and gas deposits, were published in 1939 (35). A detailed description of Mississippian rocks in the subsurface of Kansas, based on a microscopic study of cuttings and cores, and of insoluble residues, was published in 1940 (36).

The Mississippian, variously represented by different units, is found beneath the Pennsylvanian in subsurface, over most of Missouri, Iowa, and Nebraska, except where removed by early Pennsylvanian erosion, on the tops of large structural features such as the Cambridge anticline, and the Nemaha ridge, in southern Nebraska.

Mississippian rocks in the subsurface are succeeded by beds belonging to different parts of the Pennsylvanian, depending on the degree of local and regional early Pennsylvanian uplift and truncation.

PENNSYLVANIAN

Rocks of Pennsylvanian age are exposed in almost continuous outcrops, from the north flank of the Llano uplift, Texas, to north-central Iowa. Unlike the outcrops of rocks of the preceding systems and series, which are found only in major uplifts, the distribution of the Pennsylvanian is dependent largely on the regional strike. The average regional strike of the upper units is slightly east of north, but the lower beds show important eastward re-entrants in west-central Arkansas and northern Missouri.

The regional strike is modified somewhat by the structure of the Llano uplift, slightly by the Arbuckle uplift, and markedly by the Ouachita uplift and adjacent Arkansas Valley syncline. The strike is also modified, locally, by the differential effects of uplift and regional tilting on the outcrops of stratigraphic units that vary enormously in thickness, and by local changes in the rate of dip.

Further modification can be attributed to the influence of paleogeographic conditions in determining the original areas of deposition. The sea, during certain periods of Pennsylvanian time, and in certain local areas, submerged and transgressed large areas of previous uplifts. Such a condition existed in northern Missouri.

The section consists predominantly of shale, with interbedded units of sandstone and limestone, and redbeds in the upper part. Erosion on these beds of differing resistance, has produced the extensive plains, dip slopes, and conspicuous escarpments that are so characteristic of the areas underlain by Pennsylvanian beds, throughout the region. In areas of gentle dips, the escarpments are eastward-facing, long, sinuous, cuesta ridges, with broad, gentle back slopes. In the highly folded mountain areas of steeply dipping rocks, the escarpments are hogbacks, and most of the intervening shale valleys are narrow.

The Pennsylvanian section of the Mid-Continent region is one of the thickest and most complete to be found in North America. This is particularly true of the development in Oklahoma and Kansas, and unquestionably these Pennsylvanian rocks deserve the consideration of stratigraphers as a possible standard section for comparison with equivalent strata elsewhere. They combine a surprising completeness and thickness, with interbedded marine and continental facies and fairly abundant fossils. Thus direct comparisons may be made with sections elsewhere, in which either plant or animal remains predominate.

In the Oklahoma-Kansas section, the Pennsylvanian is divided into four series: Morrow, Des Moines, Missouri, and Virgil. This classification will be used as a standard of reference in this discussion. Although coördinate and correlative units are designated by different classificatory terms of varying rank, by different authors discussing different areas, the attempt is made here to fit them all into the four-fold classification described above. Author's classificatory terms, if they differ from the scheme of classification used in this paper, are indicated by quotation marks.

Throughout most of the region, Pennsylvanian rocks rest on the underlying Mississippian, with slight to great unconformity and the contact is marked in most places by faunal changes. The transition into the overlying Permian is so gradual, that even after half a century of study and controversy, the exact position of the boundary is still subject to debate.

Division between the Morrow and Des Moines series is based on conspicuous, widespread evidence of unconformity; between the Des Moines and Missouri, by slight regional unconformity, and the disappearance of the brachiopod genus *Mesolobus*, and the bryozoan *Prismopora*, as well as important fusulinids and other fossils; while division between the Missouri and Virgil is based on widespread unconformity and the first conspicuous appearance of redbeds above the unconformity.

Conglomerates in the Wapanucka and Joliff limestones, Arbuckle Mountains, and Ardmore basin, give evidence of uplift and erosion during Morrow time. This important period of folding culminated after the deposition of the Morrow beds. At this time were rejuvenated or formed the Llano uplift, Concho arch, Red River uplift, in Texas; Criner Hills, Hunton-Tishomingo uplift (1), initiation of the intervening Ardmore basin and probably the Arbuckle anticline, and the central Oklahoma uplift, in Oklahoma; Wichita-Amarillo Mountains, in Oklahoma and Texas; Nemaha ridge, and Central Kansas uplift, in Kansas; and many oil-producing structures throughout the region. As a result of this folding, the region was divided into several distinct basins in which Des Moines sediments were deposited. Two of these were separated by the Hunton-Tishomingo uplift, and two others by the Llano uplift-Concho arch.

The unconformity between the Missouri and Virgil series reflects a period of folding during which the Arbuckle anticline (western Arbuckle Mountains), the Ardmore basin and related folds were formed or rejuvenated, and the Wichitas were rejuvenated. It is probable that important orogeny took place in the Ouachita-Marathon range, at the same time.

The Morrow and lower Des Moines are represented only in Texas, Oklahoma and Arkansas, while the overlying units, though with local, small breaks, are represented universally, except where removed by recent erosion.

The Ardmore basin is the only local area where the section is at all complete, and contains nearly 20,000 feet of Pennsylvanian rocks (2). The maximum thickness of approximately 36,000 feet, is found in the combined sections of the Ouachita Mountains (3, 4, 5), Arkansas Valley syncline (6, 7), north-central Oklahoma (8), and Kansas (9).

North-central Texas.—

The entire Pennsylvanian is well represented in Texas. Rocks of this age are exposed in a great belt extending through north-central Texas from the Red River southward to the Llano uplift, and thence westward and southwestward until concealed by the overlying Permian and Cretaceous.

... The sediments occur under varying facies. In extreme north Texas and the adjacent part of Oklahoma the uppermost part of the Pennsylvanian is of the red bed facies. Southward the red beds grade into normal marine limestones and shales. . . . (10).

Cheney (11) has recently revised the classification of the Pennsylvanian section of North Texas, on the basis of faunal and diastrophic evidence, and has adjusted series boundaries to conform more closely with similar boundaries that are recognized in Oklahoma and

Kansas. According to his classification, the Pennsylvanian system is divided into Morrow, Lampasas, Strawn, Canyon, and Cisco series, and each is further divided into groups and formations.

The Morrow series is represented by the upper Barnett shale and Marble Falls limestone, which latter is of particular interest because of its considerable thickness of limestone; its peculiar fauna, which indicates transition between typical Mississippian and typical Pennsylvanian faunas; and the certainty with which it can be correlated with limestones in the lower Dornick Hills formation of the Ardmore basin, the Wapanucka limestone of the Arbuckle and frontal Ouachita Mountains, and limestones in the Morrow series of the Ozarks. The upper Barnett is equivalent to part of the Springer formation of Oklahoma (12).

The Lampasas "series" includes beds that were formerly assigned to the upper Bend and probably also includes beds that in Oklahoma have been referred to the Des Moines. The Strawn "series" embraces the remainder of the Des Moines. Cheney believes the Lampasas should be given rank coördinate with, and between, the Morrow and Des Moines series.

The Lampasas contains the Big Saline and Smithwick groups "plus some strongly folded and faulted overlying shales and sandstones (unnamed) heretofore classified with the Strawn" (13). Formerly beds now called Big Saline were considered part of the Marble Falls, and the Marble Falls and Smithwick, because of their apparent structural conformability, were bracketed in the Bend "series" or "group." Cheney presents faunal and stratigraphic evidence for splitting off the Big Saline from the Marble Falls, and for assigning the Big Saline and Smithwick to a separate major unit, which he calls Lampasas "series."

Cheney states:

... The coarse sands and conglomerates present in the Big Saline, Bostwick and Atoka beds show that their deposition accompanied or followed active orogeny.

Unconformity and faunal changes mark the plane of division between the Marble Falls and Lampasas, and between the Lampasas and Strawn. This latter, at the top of the Smithwick, has long been recognized.

The Strawn "series" is divided into the Millsap Lake and Lone Camp groups, and the latter, in its base, contains the Thurber coal, which is the principal commercial seam in Texas. The adjusted top of the Strawn corresponds with the horizon at which *Mesolobus* and *Fusulina* ss. disappear, and is marked by local unconformity between

the East Mountain shale (uppermost Strawn) and the Lake Pinto sandstone (basal Canyon).

The Canyon series, as redefined by Cheney, contains the Missouri beds, and is divided into the Whitt, Graford, Brad, and Caddo Creek groups. Its upper boundary is

... the disconformity marked by the Kisinger channel of southeast Young County. . . . It is distinguished lithologically by relatively thick limestone deposits which developed locally in bioherm or reef-like form . . . (11).

The Cisco series as defined by Cheney, is a restriction of the old Cisco "group" by lowering of the top, so that its limits now approximate those of the Virgil series, of Oklahoma and Kansas. It is divided into the Graham and Thrifty groups.

The Kisinger channel at the base of the Graham group records local erosion at least 150 feet deep into the Home Creek and Hog Creek beds. (Canyon). A red bed interpreted as a zone of weathering occurs above the Home Creek limestone over much of the region (11).

... The upper boundary of the Cisco series and the Pennsylvanian system evidently should be placed at some widespread disconformity in the Harpersville formation, above the Waldrip-Newcastle coal zone and below the *Schwagerina*-bearing "Waldrip limestone No. 3" and the Saddle Creek limestone. . . .

As thus defined, the Permian-Pennsylvanian boundary is 40-50 feet below the Saddle Creek limestone. "Harpersville" beds below this boundary are assigned to the Obregon and Chaffin formations of the Thrifty group, those above this systemic boundary to the Saddle Creek formation of the expanded Pueblo group (11).

The Cisco contains several coal seams and in addition, an abundance of coarse material that

... gives depositional evidence of the progressive growth of the Arbuckle, Wichita and Amarillo Mountains to the north during Cisco time; also the Ouachita-Marathon orogeny evidently became active during Cisco time (11).

Ardmore basin, Oklahoma.—A fairly complete section of the Pennsylvanian, comprising nearly 20,000 feet of rocks, is preserved in the highly folded Ardmore Basin, of southern Oklahoma, and is divided into the Springer, Dornick Hills, Deese and Hoxbar formations (2).

The Springer and lower Dornick Hills represent the Morrow subseries, and the former comprises a considerable thickness of shales and sandstone whose only equivalent in Texas is the upper Barnett shale (12), and that have no age equivalents in the type Morrow area of the Ozarks.

The top of the Morrow probably should be drawn at the base of the Bostwick conglomerate member, on the basis of correlating these conglomerates with coarse clastics found in the Big Saline and Atoka

beds, and on the further evidence of important, widespread unconformity below (11).

Tomlinson (14) suggests that equivalents of Cheney's Lampasas "series" probably lie between the base of the Bostwick conglomerate, and the top of the Lester limestone, thus including the middle portion of the Dornick Hills formation (2), and beds that he, R. C. Moore, M. P. White, and others, have considered to have Morrow affiliations. He further proposes to split off the upper part of the Dornick Hills, above the Lester limestone, into a new formation, called Big Branch, which, with the overlying Deese, would correlate with Cheney's Strawn "series."

The Springer formation in the Ardmore basin comprises some 3,000 feet of black, bituminous shales with ferruginous and calcareous concretions. The formation contains four conspicuous sandstone members which help to differentiate the Springer, as a mappable unit, from the underlying Caney shale of Mississippian (Chester) age. Although the Springer beds are classed as the lowermost Pennsylvanian formation in the Ardmore Basin section, it is not established that shale deposits in the upper part of the Caney, as defined, may not also belong to the Pennsylvanian series (15).

The conspicuous, named members are: Rod Club sandstone, at the base; Overbrook sandstone, 1,000 feet higher; Lake Ardmore sandstone, 400 feet or less above the Overbrook; and the Primrose sandstone, from 250 to 500 feet above the Lake Ardmore.

The upper part of the Morrow as developed in the Ardmore basin comprises beds belonging to the lower part of the Dornick Hills formation (2), up to the base of the Bostwick conglomerate. It consists principally of shale, with two important limestones: the Jolliff, at the base, and the Otterville in the upper half, and thin, calcareous sandstone and sandy limestone, above the Otterville, the whole sequence ranging from 1,100 to 1,400 feet thick.

The Jolliff limestone, 4-15 feet thick, is conglomeratic and fossiliferous, and contains numerous pebbles (up to 6 inches in diameter) of Sycamore limestone (Mississippian) and Woodford chert (Mississippian).

Overlying the Jolliff is a black shale with sideritic concretions similar to the Springer shales, which decreases in thickness from about 1,000 feet, south of Ardmore, to about 300 feet in the north part of the Ardmore basin.

The Otterville contains 25 feet or more of limestone. South of Ardmore it comprises two or three ledges of limestone with intervening shale, aggregating 100 feet or more. Oolite is common, but the most characteristic facies is a slightly ferruginous, platy, granular limestone,

composed chiefly of shell fragments. It has yielded a fairly rich, typical Morrow fauna. The limestone is conglomeratic at some of its outcrops near the Criner Hills.

Above the Otterville lie nearly 750 feet of rather light-colored shale with a few ledges of thin, calcareous sandstone and sandy limestone.

The upper Dornick Hills (restricted to beds below the top of the Lester limestone) (15) probably represent Cheney's Lampasas "series," and together with the Big Branch (new formation split off the old Dornick Hills (15), the overlying Deese formation, and the Confederate limestone member of the Hoxbar, comprise the Des Moines series of this paper, with an aggregate thickness ranging from 6,000 to 10,000 feet. The base is marked by the coarse conglomerates of the Bostwick and large unconformity below, and the top by the disappearance of the genus *Fusulina*.

The Bostwick conglomerate has a maximum thickness of 300 feet of conglomerate, sandstone and limestone, with intercalated shale. Beds of conglomerate are thickest and coarsest near the Criner Hills. They include pebbles of all older Paleozoic formations down to and including the upper part of the Arbuckle limestone (Upper Ordovician). Northward the pebbles decrease in number and size until they play out completely, north of Ardmore.

The Lester limestone, about 20 feet thick, at the top of the Dornick Hills formation, lies about 400 feet above the Bostwick, north of Ardmore but the interval increases to about 1,000 feet in the vicinity of the Criner Hills.

The Big Branch formation (manuscript name of Floyd and Nufer) is proposed (15) for the beds, formerly included in the Dornick Hills, that lie between the top of the Lester limestone and the top of the Pumpkin Creek limestone. The intervening rocks consist mainly of shale, with a marly limestone called Frensley (16), about the middle, and sandstones and shale, locally thin coal seams, a 2-foot limestone, in the upper part, and the 50-foot Pumpkin Creek limestone at the top.

The Deese formation, with a maximum thickness of almost 8,000 feet, includes the bulk of the Des Moines series in the Ardmore Basin. It is characterized by a succession of sandstone beds and chert conglomerate separated by gray, tan and red shales, with one fairly prominent limestone member, and numerous minor ones, mostly impure. Red shales dominate in the middle and upper parts of the formation, especially in the eastern and southern parts of the Ardmore Basin . . . (15).

The Deese contains the thick Devil's Kitchen sandstone and conglomerate member, about 800 feet above the base, and Arnold limestone member near the middle of the formation.

Chert-pebble conglomerates occur at three horizons in a series of massive sandstones, interbedded with shales, next above the Arnold member. The thickest and most persistent of these chert conglomerates is the Rocky Point member (manuscript map name of Guthrey and Milner) (16) 1,250 feet above the Arnold. It is possible that this member is correlative with the chert conglomerates at the base of the Wewoka formation east of Ada, Oklahoma, and with the Brazos River conglomerate in the Garner formation of the Strawn group in the Brazos River valley, north central Texas. It is about 3,200 feet below the top of the Deese formation in Lake Murray State Park (15).

Westheimer (17) suggests the correlation of the Devil's Kitchen with the top of the Savanna formation of the area northeast of the Arbuckle Mountains.

The upper 1,200 feet of the Deese formation contains somewhat less sandstone and more shale than the underlying portion, although there are at least four different conglomeratic horizons, and two limestones (Williams (16), 750 feet below the top, and Natsy (18), 500 feet below the top), in this interval (15). The top of the Des Moines extends to the top of the Confederate limestone, formerly basal member of the Hoxbar formation. It is worthy of note that the chert pebbles in the conglomerate members of the Deese, particularly of the Devil's Kitchen, decrease in size and abundance from south to north, and the enclosing units decrease in thickness in the same direction. These facts indicate that the eroding highland source of the material lay not in the Arbuckle Mountains nor Criner Hills, but somewhere at the southeast.

Evidence for drawing the lower boundary of the Des Moines sub-series in the Ardmore basin, at the base of the Bostwick conglomerate, has already been cited. Available evidence indicates that the upper boundary coincides rather closely with the top of the Deese, and Tomlinson (15) proposes to draw it at the top of the Confederate limestone, heretofore called the lowermost member of the Hoxbar "formation," thus restricting the Hoxbar by excluding the Confederate limestone, and assigning it to the underlying Deese formation.

The suggested correlation of the Devil's Kitchen conglomerate with the top of the Savanna sandstone, and the Rocky Point conglomerate with the base of the Wewoka formation of east-central Oklahoma, and with the Brazos River conglomerate of the Garner formation, of North Texas, ties the Deese to the same relative position in the Des Moines sequence in those two areas.

Girty and Roundy (19) list (station 4050) *Chonetes* (*Mesolobus*) *mesolobus* var. *decipiens* from beds that Tomlinson (2, p. 71) identifies as "uppermost Deese," and Dunbar and Condra (20, p. 168) report *Mesolobus mesolobus* var. *euampygus*, from "1000 feet below the top

of the Deese formation . . . in the Ardmore Basin of Oklahoma." *Mesolobus* has never been reported from strata above the Deese.

Tomlinson cites further evidence for drawing the upper boundary of the Des Moines:

The highest occurrence of the genus *Fusulina* in the Ardmore Basin is in the Confederate member. At the top of the member there is field evidence (southeast of Ardmore) of a minor disconformity, overlain by carbonaceous shales with traces of coal. This disconformity is taken as the top of the Des Moines (15).

Missouri beds of the Ardmore basin are wholly represented by the Hoxbar formation (restricted), which is best developed south of Ardmore, where it is about 4,000 feet thick. Conspicuous, named members are: Crinerville sandstone and limestone, 400-500 feet above the base, containing an abundance of *Triticites*; Anadarche conglomerate and limestone, about the middle; Daube limestone underlain by the only bed of coal in the Ardmore basin; and the Zuckerman sandstone about 500-1,000 feet below the top of the formation. Overlying the Zuckerman, in a small area near Hoxbar, are 500 feet of the highest exposed members of the formation (21).

Tomlinson (2) suggests that the Anadarche and Daube limestones are respectively equivalent to the Palo Pinto and Adams Branch limestones of the upper Canyon (redefined), in North Texas, and Westheimer (17) correlates the Anadarche with the Belle City limestone of central Oklahoma. The Belle City is near the top of the Missouri series as developed there, but its probable equivalent, the Dewey-Drum limestones of northern Oklahoma and Kansas, come at about the middle of the Missouri series. On this evidence it appears that the Hoxbar contains beds in its upper part that have no equivalents in central Oklahoma, and more completely represents the entire Missouri series at its maximum development.

The Virgil series is thinly and only locally represented by red shales and coarse arkose that has been referred to the Vanoss formation (2), belonging to the upper part of the Virgil. These beds are separated by great angular unconformity from the underlying, highly folded members of all stratigraphic units from Hoxbar to Springer, in the Ardmore basin, and overlap the eroded edges of the steeply dipping formations from Caney to Arbuckle, around the west end of the Arbuckle Mountains. It was the post-Hoxbar, pre-Vanoss folding that completed the formation of the Ardmore basin, the Arbuckle anticline, and related folds (1, 22). The Vanoss is overlain by the Hart limestone member of the Stratford formation, which is taken as the base of the Permian in this general area (2, 23).

Central Oklahoma.—Central Oklahoma as used here includes the area of Pennsylvanian outcrops on the east and north flanks of the Hunton-Tishomingo uplift (eastern Arbuckle Mountains), and thence north to North Fork of Canadian River.

The section is fairly complete, though the post-Morrow units are locally thinner than elsewhere, due to overlap, and feathering-out against the uplift.

The Morrow is represented by the Springer and Wapanucka formations. The Springer includes beds formerly mapped as Caney shale (24, 25), and later designated "Pennsylvanian Caney" (23). Its lower contact with the Mississippian Caney is recognizable, but exposures are difficult to find. The Springer is composed mainly of shale, but in the upper part contains the prominent Union Valley sandstone, which has been correlated with the Overbrook or Lake Ardmore sandstones of the type Springer in the Ardmore basin, with the upper part of the Jackfork sandstone of the Ouachitas and with the Hale sandstone of the Ozarks (26). The correlation of the higher Union Valley limestone with the Primrose sandstone of the Ardmore basin has been suggested by Harlton (26), and Tomlinson (14). Harlton includes an overlying shale, which he names Limestone Gap, in the top of the Springer. Evidence as to whether this classification corresponds with the original definition of Wapanucka by Taff, is not available to the writer. Morgan (23, p. 57) evidently included the Limestone Gap shale in the Wapanucka.

The Wapanucka formation is highly variable. Wallis (27) states:

The Wapanucka limestone consists of one or more beds of massive white to light brown limestone, together with chert, sandstone and shale strata. Near the town of Bromide a bed of exceptionally fine, massive oolite, 70 feet in thickness, occurs. . . .

Wallis observed unconformities at the bottom, top and within the Wapanucka. In a locality on Delaware Creek, near Bromide, he noted a limestone breccia at the top of the formation, and states:

This breccia is composed of highly angular fragments of a very dense light gray to white limestone similar in appearance of the Arbuckle limestone. . . . There are also fragments of an oolite which is very different from the Wapanucka oolite proper. . . . The oolite found in the breccia may be of Chimney-hill (*lower Hunton*)⁶ age or may belong to another formation (Viola or Arbuckle limestone) . . . (27).

A marked change in sedimentation, and important unconformity follows the Wapanucka, and it is taken as the top of the Morrow series. This unconformity marks important broad, regional folding that, in

⁶ Italics by R.H.D.

part, at least, produced the Hunton-Tishomingo uplift, Criner Hills, Wichita-Amarillo uplift, the Red River arch, and many important oil-producing structures in the Mid-Centroid region. This unconformity corresponds with the one below the Bostwick conglomerate in the Ardmore basin.

All units from the base of the Atoka formation to the top of the Holdenville shale are assigned to the Des Moines series. At the base of the Atoka is a unit consisting of shale, limestone, and sandstone, named the Barnett Hill, which probably corresponds to the upper Dornick Hills (above the Bostwick conglomerate), in the Ardmore basin, and to Cheney's Lampasas "series." Harlton points out that "This unit was locally assigned by Taff to the Atoka formation, but in other areas it was included in the Wapanucka" (26, p. 859). There is ample evidence, especially in subsurface, to indicate an unconformity above this formation, which probably corresponds to that above the Smithwick shale, between the Lampasas and Strawn "series," in Texas (11). This unconformity probably represents additional movements in the Arbuckle-Criner-Red River uplifts. The Des Moines series includes the Atoka, Hartshorne, McAlester, Savanna, Boggy, Thurman, Stuart, Senora, Calvin, Wetumka, Wewoka, and Holdenville formations, and consists mainly of alternating sandstone and shale, with a few thin limestones.

Each unit thins toward the margin of the Hunton-Tishomingo uplift, from the adjacent McAlester basin on the north and east, and thinning is accompanied by conspicuous overlap (1, 22, 23), especially in the upper units. The Atoka, Hartshorne, McAlester, and Savanna, as well as higher formations, contain prominent sandstone members, and limestone conglomerates, derived from the Hunton, Viola and Arbuckle limestones in the Hunton-Tishomingo uplift, are conspicuous in the southern and western margins of outcrops of McAlester and younger formations. These conglomerates make up part of the old "Franks conglomerate" (23, 25).

The base of the Des Moines in this area is marked by the post-Morrow unconformity already described. The genus *Mesolobus* last appears in the Holdenville, and there is evidence of local unconformity below the Seminole formation (23, Pl. XV-B). Traced northward to Kansas and Missouri, this unconformity takes on regional importance.

Only the lower part of the Missouri series is present in this area, being represented by the Seminole, Francis, and Belle City formations, and an unidentified shale of the lower Ochelata group that was included by Morgan (23) in the Vamoosa formation. Most of these units

contain limestone conglomerate in their southern margins, and show progressive overlap toward the Hunton-Tishomingo uplift. The upper Missouri is represented by an hiatus that covers a considerable time interval, before the deposition of the overlying Vamoosa conglomerate.

The Vamoosa conglomerate and sandstone, Ada and Vanoss formations are assigned to the Virgil series. Unlike the other Pennsylvanian formations of the area, the Vamoosa conglomerates are made up largely of chert fragments, with some quartzite pebbles, which attain their maximum size in T. 9 N., R. 7 E., Seminole County, indicating that their source was in some area other than the Arbuckle Mountains, and may have resulted from uplift and erosion of the Ouachita Mountains. Red beds appear for the first time as a conspicuous characteristic in the Vamoosa.

The Ada formation consists of sandstone, limestone conglomerate, and red shales. The overlying Vanoss formation is lithologically similar, but contains, in addition, large quantities of arkosic material that was derived from the erosion of the Tishomingo granite of the Hunton-Tishomingo uplift.

The top of the Virgil series, and of the Pennsylvanian system has been placed at the top of the Vanoss formation on the evidence of Permian plants found in the overlying Stratford formation (23), and on the approximate continuity of a calcareous zone in the upper part of the Vanoss formation with the Grayhorse limestone of northern Oklahoma, and the Brownville of Kansas, which is considered the top of the Pennsylvanian there (28, 29).

Ouachita Mountains, Arkansas Valley, northern Oklahoma.—Three rather distinct areas are discussed together, because the combined section is the thickest and most complete in the Mid-Continent region. In the highly folded and thrust-faulted Ouachita Mountains, the Pennsylvanian sequence begins with the Stanley and Jackfork formations (30, 31, 32, 33, 34), which Harlton (26) considers older than Morrow, and proposes to group into the Pushmataha "series." In the present discussion they are referred to the Morrow series, and are considered at least partially equivalent to the Springer. In southwestern Arkansas, the Stanley shale is underlain by the Hot Springs sandstone (31, 36), while the rest of the Morrow succession is similar to that in Oklahoma.

The Wapanucka equivalent in the Ouachita Mountains proper of southeastern Oklahoma, is considered by Harlton (26) to be the upper part of his "Round Prairie" (John's Valley) shale, which contains the interesting boulders whose lithology and contained fossils identify

them as having come from the Arbuckle, Simpson and Viola limestones, as developed in the Arbuckle Mountains. The origin of these boulders, and the manner in which they reached their present resting-place, has been the subject of much discussion (26, 31, 35). It was this shale that Taff originally named "Caney," from Cane Creek, in John's Valley, where he first studied it. It has yielded Pennsylvanian fossils that identify it as Morrow in age, equivalent to part of the Wapanucka formation. It was named Johns Valley shale by Ulrich (35).

In the frontal Ouachitas, adjacent to the Choctaw fault, the Morrow is represented by a succession of limestone with minor amounts of sandstone and shale called Wapanucka (24, 27, 37, 38), which is underlain by the Limestone Gap shale that Harlton assigns to the Springer formation (26).

The Des Moines series contains the same units as in central Oklahoma, but they are much thicker. The lower units, Atoka through Boggy, are exposed in large anticlines and synclines, in the Arkansas Valley area, extending from McAlester, Oklahoma, to Little Rock, Arkansas (6, 39). These same units thin materially between McAlester and Muskogee (40), and the Atoka and Hartshorne formations drop out in the vicinity of the latter city (40).

Units above the Boggy undergo marked changes in facies north of Arkansas River, in the latitude of Tulsa, and exact correlations of beds exposed in the areas north and south of that river are difficult. In a general way, the correlations are thought to be as follows.

The Thurman, Stuart, and Senora are probably represented by sandstones and shales in the upper Cherokee shale, cropping out east of Claremore, and extending as far north as Chelsea, where the sandstones disappear; the Calvin sandstone pinches out near Okmulgee, but is probably represented by a sandstone that immediately underlies the Fort Scott limestone, which limestone in turn, has been traced southward into the Wetumka shale; the basal sandstone of the Wewoka formation is correlated with a sandstone in the Labette shale, above the Fort Scott, and the upper member of the Wewoka underlies the Lenapah (Eleventh Street) limestone, hence is correlated with the top of the Nowata shale, making the Wewoka equivalent to the upper Labette shale, Oologah limestone, and Nowata shale; the Holdenville is correlated with the Lenapah limestone and the overlying Memorial shale (41). The fossil genera *Mesolobus* and *Prismopora* are present in the Eleventh Street limestone, which is correlated with the Lenapah limestone of northern Oklahoma and southern Kansas, and the unconformity at the top of the Des Moines is marked by the disappearance

of *Mesolobus* and *Prismopora*, the absence of the Memorial shale, north of Oologah, overlap by the Seminole formation, and local channeling at the base of the Seminole.

The Missouri series embraces units from the base of the Seminole to the base of the Nelagoney formation, and includes the Seminole, Checkerboard, Coffeyville, Hogshooter, Nellie Bly, and Dewey formations bracketed into the Skiatook group; and the Chanute, Iola, and Wann formations, Torpedo sandstone and overlying shale, Birch Creek limestone, and Weston shale, comprising the Ochelata group (8).

Too little is known of the stratigraphy and correlations of the upper Missouri and lower Virgil beds, in the area between Arkansas and North Canadian rivers, to fully comprehend their relationships. It appears that the upper Missouri beds suffered considerable truncation by pre-Virgil erosion, which cut deeper and deeper, from north to south, reaching almost if not quite to the base of the Ochelata group in Seminole County and below it in Pontotoc County. In the latitude of Wewoka, the base of the Vamoosa (Nelagoney) is separated from the Belle City limestone (Dewey-Middle Missouri) by about 30 feet of shale, whereas in the latitude of Ada, both the Vamoosa and Belle City are overlapped by the Ada formation.

The Virgil series contains the Nelagoney (Vamoosa) formation, Elgin sandstone, and Pawhuska formation, of the Douglas and Shawnee groups, and the Wabaunsee group. The top of the Virgil, and top of the Pennsylvanian, is drawn at the top of the Brownville (Grayhorse?) limestone. The most striking characteristics of the Virgil series are the apparent magnitude of unconformity at the base, the coarse, clastic nature of the basal beds, and the advent of typical redbeds. Although marine limestones and shales are conspicuous in Osage and Pawnee counties, even in that area, there are some important interbedded units of red shales and sandstones, that may be considered as typical redbeds. In Pawnee and Payne counties, a facies change similar to that along Arkansas River east of Tulsa, takes place. Through that latitude, the marine limestones and shales give way almost completely to the red shales and sandstones that are characteristic of the Vamoosa, Ada, and Vanoss formations of central Oklahoma.

Ozarks, Kansas, Nebraska.—In this area the Morrow series is represented only in northern Arkansas and northeastern Oklahoma. In Arkansas the Morrow "group" is divided into the Hale sandstone, at the base, overlain by the Bloyd shale. The contact of the Hale with the next older Pitkin limestone is marked in most places by a zone of conglomerate. In some parts of northern Arkansas, the Pitkin had

been removed prior to deposition of the Hale, and the latter is found in contact with various parts of the Fayetteville shale. The Hale itself is rather variable, consisting of sandstone, shale and limestone (42).

The Bloyd formation consists mainly of dark, carbonaceous shale, with two limestone members, known as the Brentwood and Kessler, and a thin seam of coal. The Bloyd crops out in a much smaller area than the Hale, and its most conspicuous feature is the Brentwood limestone. The limited distribution is probably due to post-Morrow erosion, and overlap by lower Des Moines beds.

The Morrow in Oklahoma is much reduced in thickness, and the Hale is the most conspicuous. The series attains its maximum thickness in Adair County, where the development of the Hale is similar to that in the type locality; in Arkansas, while the Bloyd is considerably thinner, due to truncation at the top. The Brentwood, if identifiable at all, consists of lenticular limestones, intercalated in shale, and the Kessler is thin to absent. The Kessler and much of the underlying Bloyd seem to be definitely cut off by post-Morrow erosion, in the area west of Adair County, and the basal Des Moines cuts down progressively closer to the top of the Hale (43).

Recent field investigation by Carl A. Moore, supplemented by insoluble residue studies, indicates that the massive limestone in western Cherokee, eastern Muskogee, Wagoner, and Mayes counties, usually called "Morrow," and previously considered Brentwood, is actually mostly Hale. In view of this, the Hale may represent one of the limestones of the Wapanucka formation of the Arbuckle Mountains area, rather than, or in addition to, the Union Valley sandstone, as suggested by Harlton, Hollingsworth, and others (26, 44).

In northern Arkansas and on the southwest flanks of the Ozark area in Oklahoma, the basal Des Moines beds probably belong to the Atoka formation. Lampasas equivalents have not been recognized yet in this area. Newell (40) has shown that the Warner-Little Cabin sandstone, of the McAlester formation, is in contact with Mississippian rocks, in southern Kansas, and there lies at the base of the Cherokee shale (40, p. 39).

In southern Kansas, the Des Moines series contains the Cherokee shale, Marmaton group, made up of the Fort Scott limestone, Labette shale, Pawnee limestone, Bandera shale, Altamont limestone, Nowata shale, Lenapah limestone, and Memorial shale.

The Missouri series in Kansas, is made up of alternating limestone and shales, with a few sandstone beds. It is divided into the Bourbon, Bronson, Kansas City, Lansing and Pedee groups, and each is divided into formations and members (9) which though thin, are extremely persistent, and have been traced into Nebraska and Oklahoma.

The Virgil series is distinguished by coarse, channel sandstones, at the base, and is divided into the Douglas, Shawnee, and Wabauunsee groups. These likewise have been split into many small, but persistent units that can be traced beyond state lines. The top of the Virgil and Pennsylvanian is drawn at the top of the Brownville limestone (9).

Because of the nature of the sediments, completeness, and thickness, the Missouri and Virgil section in Kansas, is the best in the entire Mid-Continent region. Southward in Oklahoma, is a gradation into indivisible units of considerable thickness, and the upper Missouri is absent. In Nebraska much of the outcrop is covered by Cretaceous and Pleistocene rocks, and in Missouri and Iowa by Pleistocene deposits.

Northern Missouri and Iowa.—The Pennsylvanian section of Missouri and Iowa is similar to that of Kansas. The Morrow, and much of the lower Des Moines series are absent. The classification into Des Moines, Missouri and Virgil series is recognized in Iowa (45), but in Missouri, post-Des Moines beds are classified as the Missouri series, which is subdivided into groups bearing many of the Kansas group names, but generally with different boundaries (46).*

In northern Missouri, the Des Moines series is divided into Cherokee and Henrietta groups, and apparently basal Cherokee beds are somewhat younger than the basal Cherokee of Kansas. These basal beds seem to have been deposited in two separate basins, one that encroached eastward from the Forest City basin, and another that encroached westward from Illinois. By late Cherokee time, the two seas merged, spreading over much of Iowa and much of Missouri, including at least part of the Ozark area, where small, isolated patches of Cherokee beds still persist (47).

Several important, commercial coals occur in the Cherokee, and at least one in the Henrietta group. In general, the Henrietta is characterized by limestone, in contrast to the shale, sandstone and coal of the Cherokee. Some of the upper units of the Des Moines known in Oklahoma and Kansas, are absent or unrecognized in Missouri, but, except locally, there is little physical evidence of pre-Missouri erosion. The faunal change that marks the Des Moines-Missouri contact in other regions is likewise evident in this area. Cline recently has described the stratigraphy of the upper Des Moines and lower Missouri beds from Kansas City, Missouri, to Centerville, Iowa, and has added many new details of stratigraphy and correlation (48).

The Missouri series consist mainly of limestone and shale, with a few sandstones and coals. On the flanks of the Ozarks, east of the main Missouri outcrops, the unconformity at the base cuts deeper than to the west and south, and is marked by several conspicuous channel

sandstones, of which the Warrensburg and Moberly sandstones, in Missouri, are best known.

The classification used in Missouri combines the Missouri and Virgil series, but the contact between the Pedee and Douglas groups, which marks the Missouri-Virgil boundary in Kansas, is drawn at the same plane in Missouri. The Iowa classification conforms to the standard, and the units that make up the Missouri and Virgil series there, are generally similar to equivalent units in Nebraska, Kansas, and Missouri.

Pennsylvanian in subsurface.—Pennsylvanian rocks underlie the entire Mid-Continent region, except where removed by recent erosion, and are of great economic importance to the oil industry because of the large amounts of oil and gas that are produced from reservoir rocks belonging to this system. The principal production in north Texas, southern Oklahoma, northwest Arkansas, and western Missouri is from Pennsylvanian rocks, and Pennsylvanian production has long been important in the producing districts of northeast Oklahoma and Kansas.

Pennsylvanian rocks have been found in subsurface, in north Texas, in all directions from the Llano uplift. A short distance to the east and south, highly indurated or metamorphosed Paleozoic sediments, including Pennsylvanian, that belong to the Ouachita facies, have been found beneath Cretaceous, indicating the northwest margin of the Ouachita overthrust.

The Morrow series, represented by the Marble Falls limestone, is present in wells throughout the area between the Llano uplift and Archer County, over the Bend flexure, whence the formation dips within a short distance eastward to depths beyond present drilling. The portion of the Marble Falls that is present in the subsurface of the Ranger district, Eastland County, has been named the Comyn formation (11).

The Morrow is absent from the Concho arch in western Coleman and Callahan counties, and in areas to the southwest, including Reagan County. It is also missing from the Electra arch, Muenster arch, and other features of the Red River uplift, and from the Amarillo uplift.

The Lampasas "series," lower part of the Des Moines series, as used here, is more widespread than the Morrow, being absent from the Reagan uplift, Electra arch and Amarillo uplift, but present in most other parts of north-central Texas. Included in the Lampasas, in the subsurface of Eastland, Stephens, Young, and adjacent counties, are several important pay zones, including the famous producing

sandstone and limestone reservoirs of Ranger, Desdemona, Caddo, and Breckenridge fields ("Caddo lime") (11). Recently discovered deeper "pays" and coarse sand and conglomerate, in Montague County, are also of Lampasas age, belonging mostly to the Big Saline (13).

The upper part of the Des Moines series comprises the Strawn "series," and rocks of this unit cover all the structural features mentioned above, except the Amarillo uplift, but are very thin on the Reagan uplift and the Concho and Electra arches. In general, the Morrow and Des Moines series, in subsurface, thicken in a short distance from west to east, the maximum being found east of the Bend flexure, in Denton County (49). This thickening is most marked in the Strawn beds. The K. M. A. and Hull-Silk oil fields of Wichita and Archer counties are the most important of many oil fields producing from rocks of Strawn age. They produce mostly from sandstone reservoirs (13).

Canyon and Cisco beds, representing the Missouri and Virgil series, are widespread in the subsurface of north-central Texas. The Palo Pinto formation, of middle Canyon, contains the important "Palo Pinto pay" of Jones and Shackelford counties (11, p. 89). Numerous other horizons belonging to both the Canyon and Cisco produce oil and gas in various parts of the area. Burkburnett and Electra are the most famous fields producing from Cisco rocks (13).

Production from Pennsylvanian rocks is important in nearly all the oil and gas areas of Oklahoma. The principal producing formations in southern Oklahoma, and northeastern Oklahoma, are of Pennsylvanian age, and Pennsylvanian sands account for an important amount of the production in Seminole, Okmulgee, Creek, Tulsa, Osage, and adjacent counties.

The Morrow series, in subsurface, is found only along the eastern margin of the central Oklahoma uplift, as far north as Okmulgee County, and contains the important Cromwell sand, and "Wapanucka lime" producing formations.

The basal Des Moines has only little wider distribution than the Morrow, and contains the Dutcher sands. Higher Des Moines beds are more widespread, and the uppermost Des Moines and younger units probably underlie the entire state. The Booch, Bartlesville-Glenn, Burbank, Prue-Calvin, and Oswego and Big limestones, are important producing formations of the Des Moines in Seminole, Hughes, Okmulgee, Okfuskee, Lincoln, Creek, Tulsa, Rogers, Nowata, Washington, and Osage counties.

The Cleveland and Layton sands are important horizons in the

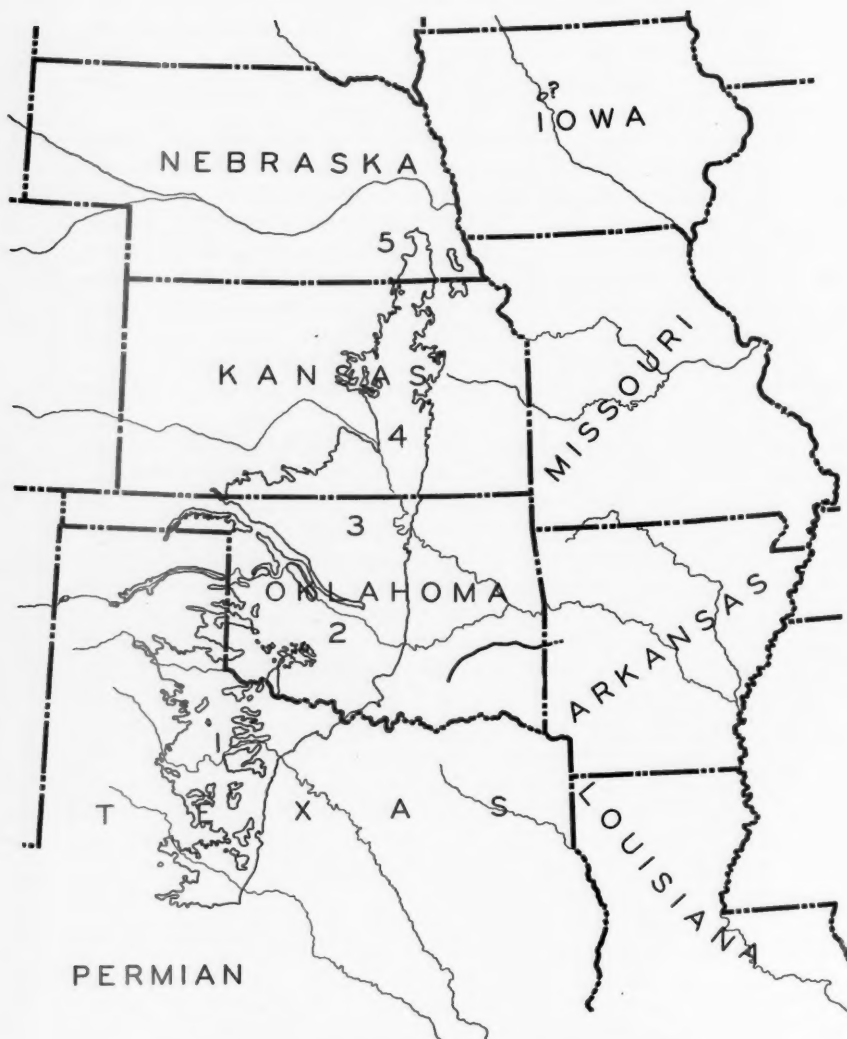


FIG. 7.—Distribution of Permian rocks in Mid-Continent region.
Numbers correspond with areas listed in Chart VII.

REGIONAL STRATIGRAPHY OF MID-CONTINENT 1679

PERMIAN											
SERIES	OLD CLASSIFICATION	1		2		3		4		5	
		NORTH TEXAS		CENTRAL OKLAHOMA		NORTHERN OKLAHOMA		KANSAS		NEBRASKA	
GAUDALUPE	MOUNTAIN	TRIASSIC		TERTIARY		TERTIARY		CRETACEOUS		CRETACEOUS	
		QUARTERMASTER		QUARTERMASTER		QUARTERMASTER		BIG BASIN		NOT	CIMARRON
		-----		CLOUD CHIEF		DAY CREEK		DAY CREEK			
		WHITEHORSE GP.		RUSH SPRINGS		WHITEHORSE		WHITEHORSE			
		MARLOW		"CUSTER GP."							
LEONARD	DOUBLE	DOG CREEK SH.		CHICKASHA -		DOG CREEK SH.		DOG CREEK SH.		EXPOSED	
		BLAINE GYPSUM		DUNCAN		BLAINE GYPSUM		BLAINE GYPSUM			
		FLOWER POT SH.				FLOWER POT SH.		FLOWER POT SH.			
		SAN ANGELO SS									
		WOLF CAMP	WICHITA	CLEAR FORK GP.		HENNESSEY -		HENNESSEY SH.		CEDAR HILLS SS	
LUEDERS GP.				GARBER -		GARBER SS.		SALT PLAIN FM.			
CLYDE GP.				WELLINGTON		WELLINGTON FM.		HARPER SS.			
BELLE PLAINS GP.				STRAFORD SH.		STILLWATER FM.		NINNESCAH SH.			
PENN.	CISCO			ADMIRAL GP.				HERINGTON LS.		HERINGTON LS.	
		PUTNAM GP.				COTTONWOOD LS.		COTTONWOOD LS.			
		MORAN GP.				FORAKER LS.		AMERICUS LS.			
		PUEBLO GP.						ADMIRE GP.			
		CISCO		VANOSS		WABAUNSEE		WABAUNSEE		WABAUNSEE	

Missouri series, and several members of the Virgil series are productive in Kay, Noble, and Garfield counties.

Pennsylvanian rocks underlie most of Kansas, and yield important production, throughout the oil and gas area. Only the upper Des Moines and younger units are present, and these thin from east to west, due to non-deposition of the lower beds and overlap onto the central Kansas uplift.

Many of the formations that produce in northern Oklahoma are also productive in southeastern Kansas. Westward the lower sands drop out, and the Missouri and Virgil beds pass over into limestones. The Kansas City-Lansing limestone of the Missouri series is the most important producer of western Kansas.

A small amount of oil and gas production is found in western Missouri, and gas is produced in the Arkansas Valley, near Fort Smith and Russellville, Arkansas. In both areas, production is probably from sands belonging to the Des Moines series.

PERMIAN

Ideas on the stratigraphy of the Permian at the present time, are probably more fluid than on any other system; hence, any classifications and correlations suggested now, are open to question and change. Considerable revision of thought on the Permian have been presented in the *Bulletin* during the past year, and the Association has authorized the preparation of a special volume on the Permian of the western interior United States—a symposium to be written under the editorship of Ronald K. DeFord. This work will doubtless modify present concepts still more, so that the correlations of the Permian included herein, to a much greater extent than the balance of this paper, are merely a summary of current opinion.

The Permian rests conformably on the Pennsylvanian throughout the region, except where Pennsylvanian rocks are absent, especially around the northwest end of the Arbuckle Mountains, Oklahoma, where the Hart limestone rests with great angular unconformity on rocks from upper Pennsylvanian to Lower Ordovician. Its outcrops lie west of the Pennsylvanian, and generally east of the Cretaceous of the Great Plains, though in Texas and Oklahoma, Permian rocks are overlain by Triassic and Tertiary. The area of Permian outcrop in the Mid-Continent region extends from the latitude of San Angelo northward to Red River, thence northeast across the west half of Oklahoma and east-central Kansas, to the southeast corner of Nebraska. A small exposure of redbeds and gypsum near Fort Dodge, Iowa, is questionably referred to the Permian.

The Permian section of the Mid-Continent region contains a complex, heterogeneous succession of beds of many lithologic facies, that does not lend itself readily to subdivision and correlation. It is characterized by continental redbeds, but contains important successions of marine, fossiliferous deposits in the northern and southern parts of the region. Laterally, these marine deposits finger out into redbeds, and in the central part of the region, principally in Oklahoma and North Texas, the section is comprised of a great thickness of redbeds, containing large lenses of sandstone of deltaic origin, which in turn grade laterally, and interfinger with red shales. The Oklahoma and North Texas section, and the upper Permian of Kansas also contains broad areas of thick shales, important deposits of gypsum and salt, and some more or less persistent beds of dolomite.

Regionally persistent stratigraphic markers are few, and such locally important markers as do exist are of limited extent, and so closely resemble other local markers that occur at different horizons, that regional correlation and classification are extremely difficult.

Recently, a committee of West Texas geologists and a sub-committee of the geologic names and correlations committee of the Association have suggested a standard section and classification for the Permian of North America, based principally on the marine sequence in southwest Texas and adjacent parts of New Mexico (1, 2). Under the proposed classification, the Permian is considered a system, and is divided into four series: Wolfcamp, Leonard, Guadalupe, and Ochoa. Each contains distinct characteristics, and correlations of bounding units with the marine sections of north Texas and Kansas, are generally agreed to by paleontologists and stratigraphers working in those areas. The application of the standard classification to the redbeds section of Oklahoma is less definite, but has been approximately established by the tracing of beds through areal mapping. Of all the series boundaries, that between the Leonard and Guadalupe, at the base of the Marlow formation of the Whitehorse group, seems to be most readily acceptable to geologists who have worked in Oklahoma.

North Texas.—Cheney in his important paper on North Texas (3), has classified the Permian rocks of that area to conform with the new standard section, and recognizes the Wolfcamp and Leonard series, and the Whitehorse group, which he does not assign to a series, but which Adams *et al.* (1) place in the Guadalupe series. The Wolfcamp is divided into the Pueblo (redefined), Moran, Putnam, and Admiral (redefined) groups, and embraces the upper Cisco, and about the lower half of the Wichita group of the older classification. The Leonard series is divided into the Belle Plains (redefined), Clyde, Leuders,

Clear Fork, and El Reno (San Andres) groups; and with the overlying Whitehorse group, of the Guadalupe series, embraces the upper Wichita, Clear Fork, and part of the Double Mountain groups of the older classification.

On the basis of evidence mainly from West Texas, Lewis (4) suggests that the El Reno (San Andres) group should be placed in the Guadalupe series, instead of the Leonard, and that the Leonard-Guadalupe boundary should be drawn at the base of the El Reno, rather than at the base of the Whitehorse group, as suggested by other workers in the area (1). West Texas geologists are far from agreement on the matter (5), and for this reason, plus the fact that in Oklahoma the El Reno-Whitehorse separation is so definite, and so much more easily recognized than the El Reno-Hennessey boundary, the classification of Adams *et al.* (1) is followed in this paper. For Oklahoma, at least, the base of the Marlow formation (Whitehorse) is the most logical plane in the entire Permian section for making a major division.

The Wolfcamp and much of the Leonard in north-central Texas exhibit a fossiliferous, marine sequence, with some intercalated evaporites. The El Reno group of the upper Leonard, on the other hand, indicates a change in sedimentation, and is typically a redbed and evaporite section.

Adjacent to Red River, north of the area studied by Cheney, marine deposits give way to the redbeds facies, and the Permian section is classified as Wichita, Clear Fork, San Angelo, Dog Creek-Blaine, and Quartermaster-Whitehorse (6).

Central Oklahoma.—A tri-partite division of the Permian in central Oklahoma was proposed by Green (7) in 1937, including the "Wannette," "Minco" and "Upper Red-Beds." The boundaries drawn for the two lower divisions appear to correspond closely with those of the Wolfcamp and Leonard series, and probably should be dropped in favor of these new standard terms (1).

The Stratford shale, including the Hart limestone, "Stillwater formation," and "Konawa formation" (8) appears to represent the Wolfcamp series; and the Leonard embraces the rocks mapped as Wellington, Garber, Hennessey, and Chickasha-Duncan (7, 9, 10, 11, 12). Around the northwest part of the Arbuckle Mountains (Arbuckle anticline), the base of the Stratford shale rests with great angular unconformity on rocks from upper Pennsylvanian to Lower Ordovician, which were intensely folded and truncated before the close of Pennsylvanian time.

The rocks called Wellington consist of an alternating, intergrading, and interfingering succession of red shales and red, cross-bedded sand-

stones. The Garber is dominantly red, cross-bedded and irregularly bedded sandstone of deltaic origin, which transgresses stratigraphic planes, and grades laterally into shale; and the Hennessey is dominantly red shale, but contains a thick sandstone lens in Garvin County, which Dott (13) called Garber. Vertebrate fossils found by Professor Stovall, of the University of Oklahoma, in the Garber and Hennessey, and the deltaic character of the Garber, indicate that these rocks are of continental and fluvial origin.

The Duncan-Chickasha beds, in the east end of the Anadarko basin, consist principally of a thick series of irregularly bedded sandstones, most of which disappear laterally, north and west, along the strike. The character of the bedding indicates deltaic origin, and considerable arkosic material is present, indicating that the material originated, in part at least, in the granite areas of the Arbuckle Mountains. The Duncan sandstone is correlated with the San Angelo of Texas.

Considerable controversy exists over the relation of the Duncan-Chickasha to beds of the El Reno group, as developed in southwestern and northern Oklahoma. One group of geologists contends that the Duncan-Chickasha is directly equivalent to most or all of the Flower Pot shale and the overlying Blaine gypsum and Dog Creek shale (14), and the relationship is one of lateral gradation from deltaic, fluvial deposits into sub-aqueous sediments. The other group contends that the Duncan-Chickasha is equivalent to the Flower Pot shale only, and that the Blaine and Dog Creek were removed by local uplift and erosion, prior to the deposition of the overlying Marlow formation (7, 12).

The Guadalupe series is represented by the Whitehorse group, including the Marlow formation, Rush Springs sandstone, and Cloud Chief gypsum. At or near the base of the Cloud Chief is the Weatherford dolomite-gypsum, which some geologists believe to be nearly or exactly equivalent to the Day Creek of northwestern Oklahoma and Kansas (15). A distinct change in lithology occurs with the Marlow and this unit is the most uniform and widespread of any in the section, making the base of the Whitehorse the most acceptable plane of division in the entire Permian sequence. The Marlow contains an interesting calcareous and dolomitic, fossiliferous bed called the Verden sandstone, which Bass (16) interprets as an off-shore bar.

Roth (17) grouped the Whitehorse and overlying beds into a unit which he called "Custer," and suggested the Permo-Triassic boundary should be drawn at the base of the Whitehorse. This view was not generally accepted, and recently Newell (18) restudied the Whitehorse fauna, and states: "... The results of this investigation clearly indicate a late Permian age for the fauna. . . ."

The Quartermaster formation, overlying the Whitehorse group, has been divided into the Doxey shale and overlying Elk City sandstone members, by Griley (19). These are generally regarded as comprising the youngest Permian rocks of the area, though their position with respect to the standard section of southwest Texas and southeast New Mexico is in doubt.

Adams and others state (1, p. 1678): "The Guadalupe series includes the Whitehorse group and equivalent beds in Texas, Oklahoma, and Kansas." Regarding equivalents of the Ochoa series, they state: "Outcrops of Ochoa age are not recognized by the writers along the eastern margin of the Permian basin in Texas or in the Texas Panhandle, and the Ochoa series appears to be absent in Oklahoma, Kansas, and Nebraska." DeFord (1, p. 1679) adds: "... Many Oklahoma and Kansas geologists ... think that Ochoa sediments are probably present in their geologic column. ..." Discussing a paper on the subsurface stratigraphy of Hugoton gas field, southwestern Kansas, by Clenon C. Hemsell, DeFord (1, p. 1680) states: "The proposed correlations suggest that the Ochoa series may be represented by a hiatus between the Day Creek and the Quartermaster, and that the Quartermaster may be Triassic."

Northern Oklahoma.—The Permian section in northern Oklahoma consists of interbedded marine and redbeds sediments, in the lower part, succeeded by redbeds and evaporites. The base of the Permian is drawn a short distance below the Foraker limestone, at the top of the Brownville limestone. The Wolfcamp series embraces the Stillwater formation, which is marked at the top by the Herington limestone. The Stillwater contains several limestone beds that have been traced into Oklahoma from Kansas, but nearly all of them lose their identity in the redbeds section, before reaching central Oklahoma.

The Leonard series includes the Wellington formation, Garber sandstone, Hennessey shale, and the El Reno group. In extreme northern Oklahoma, the Wellington consists of gray to bluish and drab shales, with numerous thin beds of gray "mudstones," but farther south is a typical redbeds formation.

The Garber sandstone is well developed in its type area, eastern Garfield County, and southward into central Oklahoma, but lenses out northward and loses its identity in red shale. On the other hand, the Hennessey shale contains considerably more sandstone than in central Oklahoma. According to Green, the Duncan sandstone does not extend into northern Oklahoma, but grades into the Flower Pot shale (20). The El Reno group, consisting of the Flower Pot shale, Blaine gypsum, and Dog Creek shale, are well developed in this area.

The relationships of the Garber sandstone, sandstones in the Hennessey, and the Duncan-Chickasha sandstones, indicate the lenticular and deltaic nature of these sediments, and the difficulties encountered in attempting correlations, and in establishing a satisfactory classification.

The Guadalupe series is represented by the Marlow and Rush Springs formations, and possibly the Cloud Chief, with much the same development as in central Oklahoma, except that the Marlow is more sandy, and the Rush Springs contains more shale. Although Gould (21) originally correlated the Day Creek dolomite of northwestern Oklahoma, with the Weatherford at the base of the Cloud Chief, in west-central Oklahoma, Evans (22) believes that the Day Creek overlies the Cloud Chief. Other workers (15) believe that the Day Creek is equivalent to the Weatherford dolomite-gypsum, or to twin gypsums approximately 30 feet above it, hence is at the base, or in the lower part of the Cloud Chief.

Gould (23) originally defined the base of the Day Creek as the top of the Whitehorse, and subsequently, the Cloud Chief was included in the "Whitehorse group," a usage that has become rather firmly fixed. A final decision as to the proper classification and nomenclature of these units can not be made until the question of the position of the Day Creek with respect to the Cloud Chief is settled. For the present purpose, the section in Chart VII, column 3, is given following Noel Evans (22, p. 408). Subsequent work may show that some of the strata now classed as Quartermaster in northwestern Oklahoma, and Big Basin in Kansas, should be referred to the Cloud Chief.

The Quartermaster is generally covered by Tertiary in northwestern Oklahoma, north of Canadian River, and the highest Permian rocks throughout this area and the eastern Panhandle, are mapped as Cloud Chief, but the sandy nature of many of the exposures in Beaver and eastern Texas counties suggest the possibility that the Quartermaster is represented.

Kansas.—The lower, marine Permian, comprising the Wolfcamp series in Kansas, has been carefully studied, and known for many years. The base of the Wolfcamp is drawn at the top of the Brownville limestone, and the top is placed at the top of the Herington limestone, which falls in the middle of the Summer group. Thus the Wolfcamp includes the Admire, Council Grove, Chase, and lower Sumner groups. Owing to overlap by the Cretaceous, Permian rocks above the Sumner group are not exposed north of central Kansas.

Norton (24) has given a very detailed discussion and classification of the redbeds above the Wolfcamp, exposed in southern Kansas, in

which the section is divided into a number of groups, formations, and members.

According to this classification, the units comprising the Leonard series are: Wellington shale; Ninnescah shale; Stone Corral dolomite; Nippewalla group, including the Harper sandstone, Salt Plain formation, which underlies the Great Salt Plain near Cherokee, Alfalfa County, Oklahoma, Cedar Hills sandstone, and Flower Pot shale; Blaine gypsum; and Dog Creek shale.

Owing to lateral gradation of the sediments, the task of correlating these subdivisions of the Leonard with time equivalents in Oklahoma is extremely difficult and unsatisfactory. The Wellington shale has been traced for a considerable distance into Oklahoma, and the Blaine gypsum and Dog Creek shale have been traced southward still farther. Correlations of intervening units are only approximations.

The Guadalupe series is represented by the Whitehorse formation and Day Creek dolomite. Norton divides the Whitehorse into the following members, from the base upward: Marlow, Relay Creek dolomite, an even-bedded sandstone, and an upper shale member. The Relay Creek is regarded as a member of the Marlow in central Oklahoma (25), and Norton correlates the even-bedded sandstone and upper shale with the Rush Springs-Cloud Chief, of Oklahoma.

Overlying the Day Creek dolomite are 65 feet of redbeds which Cragin named Hackberry shales and Big Basin sandstone. The name "Hackberry," being pre-occupied, has been dropped but "Big Basin" has been retained, and because these strata can be considered one formation of sand beds interstratified with beds of silty and sandy shale, the writer considers them to be essentially one formation and includes all beds between the Day Creek dolomite and the top of the Permian redbeds of Kansas (here covered by Cretaceous) under the name "Big Basin formation." . . .

Should further work establish the correlation of the lower shaly part of the formation with the Doxey shale member of the Oklahoma Quartermaster formation, the Big Basin name should be restricted to the sand beds alone, the possible equivalent of the Elk City sandstone member of the Quartermaster. At present, however, the inter-relations of the type Quartermaster with the Day Creek dolomite and the so-called "Cloud Chief" member of the Whitehorse have not been definitely established; therefore the writer believes that Evans was not justified in attempting to drop the Kansas nomenclature, which has the distinct advantage of priority and ready reference to the enclosing strata (24, p. 1813).

Nebraska.—The Wolfcamp series, represented by the Council Grove, Chase, and lower Sumner groups, and 9 feet of the Pearl shale, overlying the Herington limestone, and belonging to the Leonard, are the only Permian rocks exposed in Nebraska. Younger units are covered beneath the Cretaceous overlap. Outcrops are found in the

southeast corner of the state, in Gage, Johnson, and Pawnee counties, and in synclinal outliers in Nemaha and Richardson counties. The development of the lower Permian in Nebraska is similar to that in Kansas, and the section is composed principally of marine, fossiliferous limestones and shale.

Iowa.—Redbeds and gypsum, questionably referred to the Permian, are exposed along the Des Moines River, near Fort Dodge, Webster County, Iowa.

Permian in subsurface.—Permian rocks are encountered in drilling in all portions of the Mid-Continent region west of their outcrop, and are of great economic importance because of the large volumes of oil and gas that have been produced from them.

Study of logs and samples from hundreds of wells that have been drilled in West Texas, Texas and Oklahoma panhandles, western Oklahoma, and western Kansas, indicate a southwestward transition from redbeds facies into evaporite and marine deposits, and the development, in West Texas, of a deep basin, containing several thousand feet of limestone, dolomite, anhydrite, and salt.

The principal beds of salt have been found to rise in the stratigraphic section from northeast to southwest. In Kansas, the principal salt bed is found in the Wellington, correlated as the lower part of the Leonard series; in the Texas Panhandle, the main salt is above the middle of the Leonard; and in West Texas, it is found in the lower part of the Guadalupe series.

All three districts present a similar sequence of rocks, beneath the salt: anhydrite, underlain by dolomite and limestone, with some local sandstone beds, and oil and gas production is found in the latter three. In the Texas Panhandle, the anhydrite and underlying dolomite are collectively called the "Panhandle big lime."

The principal oil and gas districts that produce from the Permian rocks are: Midland basin of West Texas; Texas Panhandle, with oil and gas production in both the "Big lime," of lower Permian age, and in granite wash of upper Pennsylvanian age; gas in the Oklahoma panhandle and southwestern Kansas (Hugoton field); and oil and gas in several fields in southern and north-central Oklahoma, including Cement, Chickasha, the general Duncan-Ardmore area, and shallow sands in pools in Garfield, Noble, Kay, and Grant counties. Oil in Pennsylvanian and older rocks is produced also in most of these Oklahoma areas.

MESOZOIC ROCKS

Mesozoic rocks, consisting of representatives of the Triassic, Jurassic and Cretaceous systems, are exposed in the southern, western, and



FIG. 8.—Distribution of Mesozoic rocks in Mid-Continent region. Cross-hatching denotes outcrops of Triassic and Jurassic. Solid areas denote Cretaceous. Numbers refer to areas listed in Chart VIII. Type locality of Dakota sandstone is near Dakota City, Nebraska.

MESOZOIC

	1	2	3	4	5
	CENTRAL & NW. TEXAS	NE. TEXAS SO. OKLAHOMA	OKLAHOMA PANHANDLE	KANSAS NEBRASKA	IOWA
	EOCENE	EOCENE	PLIOCENE	PLIOCENE	PLEISTOCENE
UPPER CRETACEOUS (GULF SERIES)	NAVARRO GP TAYLOR GROUP AUSTIN GROUP EAGLE FORD GP 	NAVARRO GP. TAYLOR GROUP AUSTIN GROUP EAGLE FORD GP. WOODBINE GP	(HIGHER BEDS PRESENT)	MONTANA PIERRE SH COLORADO NIOBRARA FM. CARLILE SH. GREENHORN LS GRANEROS SH	COLORADO GP
			DAKOTA SS.	DAKOTA SS.	DAKOTA SS.
LOWER CRETACEOUS (COMANCHE SERIES)	WASHITA GP. FREDERICKSBURG TRINITY	WASHITA GP FREDERICKSBURG GP TRINITY GP	PURGATOIRE FM. 	BELVIDERE FM CHEYENNE SS	
JURASSIC	MORRISON (LOCALLY)		MORRISON FM. EXETER SS.		
TRIASSIC	DOCKUM		DOCKUM		
	PERMIAN	PENNSYLVANIAN- PRE-CAMBRIAN	PERMIAN	PERMIAN	PENNSYLVANIAN- PRE-CAMBRIAN

CHART VIII.—Subdivisions, nomenclature, and best available correlations of Mesozoic rocks in different areas.

northern parts of the Mid-Continent region. Outcrops of Triassic and Jurassic formations are limited in areal extent to the margins of the High Plains. The former is found only in the panhandles of Texas and Oklahoma, and one small outcrop in the southwest corner of Kansas, and the latter in the panhandle of Oklahoma, and one small outcrop in the northwest corner of Texas. The Cretaceous, on the other hand, crops out in wide areas in Texas, southern Oklahoma, southwestern Arkansas, western Kansas, eastern Nebraska, and western Iowa.

TRIASSIC AND JURASSIC

The Triassic is represented by the Dockum group, which is composed entirely of non-marine redbeds, of upper Triassic age. It overlies the Permian, probably unconformably, and is overlain unconformably by upper Jurassic, in Dallam County, Texas (1), and Cimarron County, Oklahoma (2); by Jurassic (?) in Texas County, Oklahoma (3); by Tertiary in the Texas Panhandle; and by Cretaceous, on the southern margin of the High Plains, in Howard, Mitchell, Sterling, and Nolan counties, Texas (1, 4).

Texas Panhandle.—

Correlations of the Texas Triassic are attended with many difficulties. In the absence of zonal fossils, criteria used for correlation have been mainly stratigraphic and lithologic. The proposed units of the Triassic in Texas may be arranged as follows:

<i>Eastern New Mexico (Darton)</i>	<i>Southern Panhandle (Adams)</i>	<i>Southern Panhandle (Hoots)</i>	<i>Central Panhandle (Drake)</i>	<i>Northern Panhandle (Gould)</i>
Chinle shales	Chinle shales	Upper red clay	Sandy clay, some sandstone	(Thin or ab- sent)
"Santa Rosa" sandstone	"Santa Rosa" sandstone	Basal red clay and sandstone	Sandstone and conglomerate, some clay	Trujillo sand- stone and shale
(Generally ab- sent)	Basal shales	(Generally ab- sent)	Sandy clay	Tecovas basal shale

Roth has proposed that his Custer formation, with material formerly considered the upper part of the remaining Permian be considered lower Triassic (4).

The Dockum has yielded many vertebrate fossils in Texas.

Marine upper Jurassic deposits, called the Malone formation are known in Hudspeth County, southwest Texas, and

The non-marine Upper Jurassic Morrison beds are mapped as extending eastward beneath the northwestern margin of the Llano Estacado practically to the northwestern corner of Texas. They have not been reported from

Texas, but the fact that they are known in northeastern New Mexico and in Cimarron County, Oklahoma, only a few miles from the Texas line, make it appear possible that they will be found, perhaps with Upper Cretaceous formations, in synclines in the northern Llano Estacado (4).

The geologic map of Texas shows a small area of Morrison near Buffalo Springs, Dallam County. It is described in the legend as clay.

Oklahoma Panhandle.—Redbeds classed as Triassic (?), and questionably referred to the Dockum, crop out in several small areas along Beaver River and its tributaries, in central Texas County (3).

Gould originally classed these beds as "Red Beds of Uncertain Relationships," and later as Triassic (?), out of deference to the opinions of other geologists, but with the reservation that he was more inclined to consider them of Permian age (3).

Rocks that may be of Jurassic age occur unconformably above the Triassic (?) in a small area in central Texas County. They consist of a lower sandstone-conglomerate unit and an upper redbed unit consisting principally of shale. They underlie a sandstone from which Lower Cretaceous fossils have been obtained (3).

In northwestern Cimarron County,

The Dockum formation of the Triassic is the oldest series of rocks exposed in the area. This may be seen to underlie the Exeter (Jurassic) with slight angular unconformity. . . . The Dockum consists of gray and maroon sands and clays, agreeing in this respect with the Dockum of Big Spring, Texas, and elsewhere. . . .

The Exeter is dominantly a white, massive sandstone about 18 feet thick. . . .

The Morrison rests conformably on the Exeter and is the most widespread surface formation in the valley of the Cimarron. Lee's description "uniformly variable," is most applicable. . . . At several localities, the bedding of the Morrison makes a decided angle with that of the overlying Purgatoire of the Lower Cretaceous (2).

Stovall has collected many vertebrate fossils, principally dinosaurs, from the Morrison in Cimarron County. He found phytosaurs in the Dockum, in northeastern New Mexico, a few miles west of the Oklahoma line.

Kansas.—One small patch of Triassic (?) redbeds is shown on the geologic map of Kansas (5), about 8 miles north of Elkhart, Morton County. It is overlain by Cretaceous.

CRETACEOUS

Rocks classed as Lower Cretaceous are found in all states here included in the Mid-Continent region, except Nebraska and Iowa, and Upper Cretaceous is recognized in all the important outcrop areas. In

central and northeast Texas, and adjacent parts of Oklahoma and Arkansas (northern Gulf Coast region), the Lower Cretaceous rocks are classified as the Comanche series, and the Upper Cretaceous rocks are classified as the Gulf series. They dip east, southeast, and south, into the East Texas basin. In Kansas and Nebraska, equivalents of the Gulf series are classified as Dakota, Colorado, and Montana groups. The basal contact of the Cretaceous is everywhere unconformable, and overlies rocks from Jurassic to pre-Cambrian in age.

Central Texas.—In central Texas, the Comanche series is divided into the Trinity, Fredericksburg, and Washita groups, and the Gulf series into the Woodbine, Eagle Ford, Austin, Taylor, and Navarro groups.

The Trinity group in central Texas, as in northeast Texas, southern Oklahoma, and southwest Arkansas, is an overlapping unit, resting on rocks that vary in age from Triassic (southern High Plains) to pre-Cambrian (Llano uplift).

The Trinity group contains the Travis Peak sand and the Glen Rose limestone. Northward, the Paluxy sand comes in above the Glen Rose limestone, probably as a younger formation, though perhaps, as suggested by some writers, as a lateral, sandy variant of the upper Glen Rose (4).

In the Edwards Plateau area, the overlying Fredericksburg group is mostly limestone, and consists of the Walnut clay (thin), Comanche Peak and Edwards limestones. The latter contains large reef deposits.

The next younger Washita group consists of the Georgetown limestone, the Grayson clay, and the Buda limestone. This latter is absent in many exposures, indicating an unconformity at the top of the Lower Cretaceous.

In central Texas, the Woodbine, basal unit of the Upper Cretaceous, or Gulf series, is absent, and the section is subdivided into the Eagle Ford (black shale), Austin (chalk), Taylor (marl, clay, and sand), and Navarro (marl, sand, and clay) groups. These groups are further divided into formations.

The Navarro is the uppermost group of the Upper Cretaceous in the Texas-Arkansas-Louisiana region, and is unconformably overlain by various overlapping Tertiary formations of Midway or Wilcox age . . . (4).

Northeast Texas, Oklahoma, and Arkansas.—Cretaceous rocks are exposed in a wide, northeast-southwest band, as far north as the latitude of Dallas and Fort Worth, whence the strike changes to a little north of east, around the East Texas basin, and the outcrops pass north of Red River, into Oklahoma. They underlie the area east of Ardmore, and south of the Arbuckle and Ouachita mountains, and

extend about 90 miles into Arkansas, to Arkadelphia, where they are overlapped by Eocene beds. Cretaceous beds are also exposed in a narrow band, about 30 miles long, in Independence and Lawrence counties, east of Batesville, northeast Arkansas (6).

The same general units of the Cretaceous known in central Texas, are also recognized to the north and east, though there is considerable variation in the lithologic development, and different local names are applied to the smaller units.

In northeast Texas, the Trinity group consists of the Travis Peak sand, Glen Rose limestone, and Paluxy sand; it is undifferentiated in southern Oklahoma; and in southwest Arkansas, contains the De-Queen and Dierks limestone lentils.

At the south, the Fredericksburg group contains the Walnut clays, Comanche Peak limestone, and Edwards limestone. Adkins (4) and Thompson (7) place the Kiamichi clay as the upper formation of the Fredericksburg group, but other geologists (8, 9) class it as basal Washita.

At the north, the Walnut is very sandy, and merges with the underlying Paluxy sand. It is not recognized in Oklahoma or Arkansas. The Edwards thins, and disappears near Fort Worth, so that the Fredericksburg group is represented in extreme northeast Texas, Oklahoma, and Arkansas by only the Comanche Peak limestone, which is there called Goodland. This extends eastward to the extreme northwest corner of Little River County, Arkansas (6).

The Washita group contains the Kiamichi clay, Duck Creek marl and limestone, Fort Worth limestone, Denton marl, Weno sandy and calcareous clay, Pawpaw sandstone, Main Street limestone, and Grayson marl. The Buda limestone, youngest formation of the Washita group, seems to be absent in this area, though some geologists believe it may be represented by limestone in the upper Grayson (4). Bullard recognizes the same formations in southern Oklahoma (10). Only the Kiamichi is exposed in a small outcrop in northwest Little River County, Arkansas, where it is mapped with the underlying Goodland (6).

The standard groups of the Upper Cretaceous, or Gulf series (Woodbine, Eagle Ford, Austin, Taylor, and Navarro) are recognized in this area, but the nomenclature of some of the smaller subdivisions is somewhat different.

The Woodbine outcrop extends from the vicinity of Waco (where it is overlapped by the Eagle Ford) northward to Red River, near Gainesville, thence turns northeast and extends across southern Oklahoma to the vicinity of Hugo, where it again crosses Red River

into Texas, then re-enters Oklahoma, and crops out in southern Choctaw County. In McCurtain County the Woodbine and the overlying Eagle Ford are bracketed together as the Bingen formation (11). The Eagle Ford is not recognized in southwest Arkansas, and the Woodbine extends only to Murfreesboro, where it is overlapped by the Tokio formation (Austin).

The Woodbine is generally a sand formation, with some clay. In McCurtain County, Oklahoma, and southwestern Arkansas, it contains much tuffaceous material, and in Arkansas, considerable gravel near the base. Both the lower and upper contacts are unconformable in many places.

The Eagle Ford outcrop passes northward through Austin, and parallels the Woodbine to Red River, thence turns east, across northeast Texas, with a small, synclinal outlier in Bryan County, Oklahoma, and is mapped with the Woodbine, as the Bingen formation, in McCurtain County, Oklahoma. It is overlapped by the Bonham formation of the Austin group in Red River County, Texas, and does not crop out in Arkansas.

Outcrops of the Austin group parallel the Eagle Ford, and extend to Arkadelphia, Arkansas, where Austin strata overlap older Cretaceous, and rest on Carboniferous units and are in turn overlapped by the Eocene.

The Austin is divided into Bonham clay, Blossom sand, and Brownstown marl, in northeast Texas (1), and equivalents are called Tokio and Brownstown in Arkansas (6, 12). No Cretaceous rocks younger than Eagle Ford are present in southern Oklahoma.

From the vicinity of Temple to Red River County, Texas, the Taylor group consists of an unnamed marl at the base, succeeded by the Pecan Gap chalk, Wolfe City sand, and an upper unnamed marl. The Wolfe City pinches out in Delta County, and in Red River County, Texas, the Taylor is divided into an unnamed marl, overlain by the Annona chalk (1).

In southwest Arkansas, the Taylor equivalents include, in ascending order: Buckrange sand, Ozan formation, Annona chalk, Marlbrook marl, and Saratoga chalk (12). The Navarro group is undifferentiated in northeast Texas, and contains the Nacatoch sand, overlain by the Arkadelphia marl, in Arkansas.

Oklahoma Panhandle.—In extreme northwestern Cimarron County, Oklahoma, the Purgatoire formation (Washita age) succeeds the Jurassic Morrison formation, unconformably. The Purgatoire is divided into the Cheyenne sandstone, overlain by the Kiowa shale, which contains large numbers of the Washita fossil, *Gryphaea cor-*

rugata. The top of the Purgatoire is channeled in many places, indicating an erosion interval prior to deposition of the overlying Dakota sandstone (2). The Purgatoire is also mapped in isolated patches in northwest Dallam County, Texas (1), and Washita beds, probably Kiowa shale, are exposed on Cienguilla Creek, southwest Cimarron County, Oklahoma (11).

In central Texas County, are two small patches of fossiliferous sandstone, overlying Jurassic (?) redbeds. The fossils were identified by Bullard and Stanton as Washita in age (3). In the same locality, what appear to be slump blocks of gray shale containing *Gryphaea corrugata* indicate the presence of Kiowa shale in that vicinity.

Several isolated outcrops of rocks containing lower Cretaceous fossils, and resting on Permian redbeds, occur in western Oklahoma, north of the Wichita Mountains, and east of the High Plains. Loose fossils characterize many of the deposits, but in three areas (north of Supply, in Harper County; the Seiling-Cestos area, in Dewey, Woodward, and Major counties; and the Butler-Foss area, in Custer and Washita counties) distinct outcrops of fossiliferous limestone and clay are present. *Gryphaea corrugata* is the most common fossil, and the beds are thought to be referable to the Kiowa shale. In some localities, the basal beds, in contact with the Permian, are coarse to conglomeratic sandstone, which may represent the Cheyenne (13).

In northwest Cimarron County, the Kiowa shale is overlain unconformably by the Dakota sandstone, and it in turn is succeeded by shale containing a few thin, fossiliferous limestone, which Stovall refers to the Graneros formation (2), but may belong to the Greenhorn. Blocks of sandstone that resembles the Dakota in lithology, are found in central Texas County, suggesting that the Dakota may once have cropped out in that area (3). The Dakota is well exposed along Cienguilla Creek, southwest Cimarron County, Oklahoma.

Kansas-Nebraska.—Cretaceous rocks are exposed in about one-third the area of Kansas, and are probably present beneath a cover of Tertiary and Quaternary beds throughout an equal area. The east limit of the outcrops extends from Oklahoma-Kansas line, in Comanche County, northeast to the Kansas-Nebraska line, in Washington County; and Cretaceous rocks are exposed thence west to the Kansas-Colorado line, except where covered by younger beds.

Except for a small patch of Triassic (?) redbeds along Cimarron River in southwest Morton County, the Mesozoic in Kansas is represented entirely by Cretaceous rocks, and they belong principally to the Upper Cretaceous.

The oldest Cretaceous unit is called "Dakota group," and includes

the Cheyenne sandstone and Belvidere formation, of the Lower Cretaceous (essentially Purgatoire formation); and the Solomon and Ellsworth formations of Upper Cretaceous age (5) (probably the Dakota of Oklahoma).

Overlying the Dakota in ascending order, are: Graneros shale, Greenhorn limestone, Carlile shale, and Niobrara formation, making up the Colorado group. The Niobrara is divided into the Fort Hays limestone and Smoky Hill chalk. The Montana group is represented by the Pierre shale.

In Nebraska, Cretaceous rocks crop out in most of the eastern third of the state, and up the Republican River to the Nebraska-Colorado line. The Cretaceous is also exposed in a large area in the valley of the Niobrara River in north-central and northwestern Nebraska. The sequence of Cretaceous rocks consists of Dakota, Benton (Graneros, Greenhorn, and Carlile), Niobrara, and Pierre (14). The type locality of the Dakota sandstone is in Dakota County, north-eastern Nebraska (15).

Cretaceous rocks, represented by the Dakota sandstone, and shales and chalk of the Colorado group, crop out in northwestern and west-central Iowa, in places where the Pleistocene cover has been removed by erosion.

Mesozoic in subsurface.—Mesozoic rocks are found by drilling in areas away from their outcrops. The Cretaceous is of great economic importance, because of the important oil fields that produce from reservoir rocks of this age. Some Cretaceous formations are also important sources of underground water.

The oldest Mesozoic rocks are found in Ouachita County, Arkansas, where they comprise a redbed-salt-anhydrite-limestone sequence of Jurassic age, about 3,000 feet thick. Southward, in Louisiana, they grade into offshore, marine strata, with a maximum thickness of 7,000 feet. They do not crop out anywhere in the Gulf region. These strata had been tentatively referred to the Permian, because of their lithologic character, but Imlay (16) has recently assigned them to the Jurassic.

The section begins at the base with the Moorehouse shales, which are absent in Arkansas, where the basal unit is called Eagle Mills, and consists of redbeds, grading southward into salt. Higher units have been named in successive order: Smackover limestone, Buckner formation, and Cotton Valley formation. The top of the Jurassic is tentatively drawn at the top of the Cotton Valley.

Relative to the age of these rocks, Imlay (16) states:

The Morehouse formation is probably of Jurassic age as indicated by the

occurrence of a fossil sponge . . . in the type section. This sponge probably belongs in the family *Staurodermidae* which is known only from the Jurassic . . .

The Eagle Mills formation has been tentatively assigned by various writers to periods as removed as Permian, Upper Triassic, and Lower Cretaceous. Possibility of a Jurassic age has been suggested by Sellards and Grabau. The writer considers its age as Jurassic. This age is indicated by the occurrence of a fossil sponge obtained from the highest . . . unit of the Morehouse formation . . . immediately below Eagle Mills red beds. . . . Likewise, the conformable relations of the Eagle Mills formation with the Smackover formation, which is of Upper or Middle Jurassic age, suggests that it is nearly the same age. . . .

Additional reasons for considering the Eagle Mills formation of Jurassic age are furnished by comparisons with the Jurassic sections in southern Mexico and bordering Central American countries. . . .

Fossils from the Smackover formation show that its age is Middle or Upper Jurassic. . . .

A list is given of significant pelecypod and gastropod genera that have been found in cores from the Smackover limestone, which are found in Middle or Upper Jurassic rocks elsewhere.

. . . It is probably significant that none of the species from the Smackover formation is identical with described upper Upper Jurassic species from Mexico and Texas but that several are very similar to species from Middle Jurassic and lower Upper Jurassic of Europe.

The Buckner formation is considered part of the same sedimentary sequence as the Smackover limestone because of its conformable relationships. . . . It is, therefore, probably about the same age as the Smackover limestone and presumably Upper Jurassic.

The age of the Cotton Valley formation, on the basis of stratigraphic position, must be either late Upper Jurassic or early Lower Cretaceous. . . . The few fossils that have been obtained from the Cotton Valley formation suggest Jurassic age. One species of *Pseudomonotis* from the lower part of the Cotton Valley formation is nearly identical with an undescribed species from the Kimmeridgian stage of the Upper Jurassic of Mexico.

Other evidence in favor of Jurassic age of the Cotton Valley formation consists of two species referable to *Tancredia*. The genus ranges from Triassic to Cretaceous, but is rather rare except in the Jurassic. One of the species from the Cotton Valley formation belongs to the group *T. planata* . . . which has been recorded only from the Middle and Upper Jurassic.

. . . Reeside and Stanton examined . . . cores and reported fresh water and brackish water mollusks which do not form a definite basis for an age determination but which "seem to be not older than Cretaceous". . . . M. N. Broughton has expressed the opinion to the writer that some of the microfossils of the Cotton Valley formation suggest a Jurassic rather than a Cretaceous age. These microfossils are now being studied and may furnish the deciding evidence. The writer is inclined to favor Jurassic age for the Cotton Valley formation.

Comanche rocks are encountered by the drill in southwest Arkansas and northwest Louisiana, and some of the units are productive of

oil and gas in several fields. The upper contact with the Gulf series is marked by an angular unconformity of considerable magnitude. The Glen Rose formation of the Trinity group contains a massive anhydrite bed.

The Woodbine sand, basal member of the Gulf series, is the most important producing formation of northeast Texas, accounting for most of the production in the fields along the Mexia fault zone, in the Van pool, and the East Texas field. The Blossom-Tokio (Austin group), Buckrange and Ozan (Taylor), and the Nacatoch (Navarro) sands are also important producing formations in northeast Texas and adjacent parts of Arkansas and Louisiana.

In central Texas considerable oil is produced from the Edwards limestone (Fredericksburg group).

With the exception of small, shallow wells producing from the "Arbuckle" sand of Trinity age, in Marshall County, Oklahoma, production of oil and gas from Mesozoic rocks in the Mid-Continent region as herein defined, is restricted to the northeast Texas-Arkansas-Louisiana area.

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EXERCISE ON AMOUNT OF SOURCE BED REQUIRED TO FURNISH OKLAHOMA CITY OIL POOL¹

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ABSTRACT

The Cherokee shale is used as a hypothetical source bed for the Oklahoma City oil reserve of 600 million barrels.

By using certain assumptions about the original organic content, the percentage converted to crude oil, the loss of oil during migration and a factor for compaction, the radial extent of the shale, west of the fault, is calculated to be 7.86 miles and the volume of the shale is calculated to be 3.5 cubic miles.

A hypothetical calculation of the areal extent and the volume of a source bed required to supply the oil of the Oklahoma City pool, makes an interesting speculation.

Brief mention is made of the two schools of thought relative to the source and accumulation of this oil. Clark³ and others favor the theory of abundant accumulation of the source material, near or in the present producing formations. This argument is supported by the fact that many favorable structures, folds, and sand lenses with porosity are found barren. The other school of thought, as applied to the Oklahoma City pool, favors the theory of wide dissemination of source material and extensive migration with the conclusion that the oil is Ordovician in age.

Asphaltic sand⁴ was found on the old Simpson land surface which is evidence that some Ordovician oil did accumulate on this structure before the upper Cherokee sediments buried the old land surface. The amount of this asphaltic sand does not appear sufficient to indicate that a large volume of oil escaped through the Simpson outcrops in pre-upper Cherokee time. The evidence that these asphaltic sands formed a seal, sufficient to account for the accumulation of the present oil pool, also, appears to be wanting. However, the theory that this oil is Ordovician and that the source material was widely disseminated might be supported by the concept that the long time interval, Ordovician to upper Cherokee, was necessary for the coalescence of the generated oil; or probably a more plausible approach would be to consider that the exposure of the Simpson beds provided the impetus for

¹ Manuscript received, January 25, 1941.

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³ Frank R. Clark, "Origin and Accumulation of Oil," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), pp. 309-35.

⁴ D. A. McGee and W. W. Clawson, "Geology and Development of the Oklahoma City Field, Oklahoma County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 10 (October, 1932), p. 957.

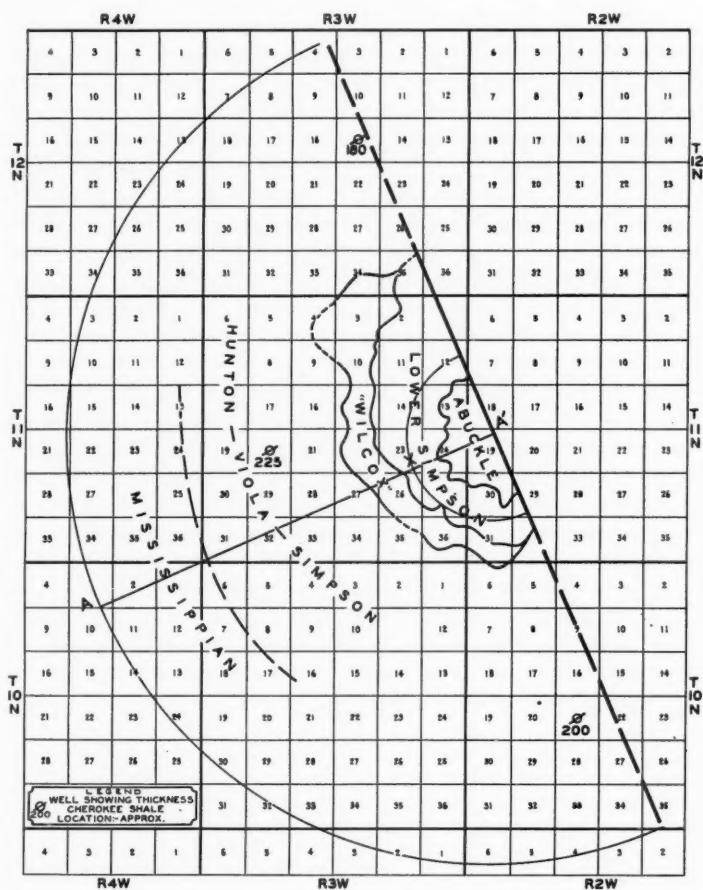


FIG. 1.—Sketch map of the Oklahoma City pool, showing distribution of formations prior to deposition of Cherokee shale (modified after McGee and Clawson, and others).

the migration with the upper Cherokee shale "saving the day" before substantial damage resulted. Many geologists seem to be of the opinion that the Oklahoma City oil accumulated after the old erosion surface was buried.

For the convenience of this exercise it is assumed that the Cherokee shale is the sole source of the oil. Similar methods of calculation could be applied to the Simpson group, the Chattanooga shale, and other possible source beds.

The general relationship of the Cherokee shale in the Pennsylvanian system to the oil-bearing beds of the Simpson group and of the Arbuckle limestone in the Ordovician system is shown in the cross section (Fig. 1). The Cherokee overlies a profound unconformity and is in contact with each oil-bearing bed in some part of the field.

The writer's premise is that there was a prolific accumulation of organic matter in the Cherokee sea which was preserved for petroleum genesis. The Cherokee was laid down on the old porous, permeable, pre-Pennsylvanian land surface, entirely burying the structure in late Cherokee time. The overburden being supplied, the resulting compaction of the shale, capped with the Oswego limestone, would move the primordial crude oil into the porous beds below the unconformity. It is suggested that the oil would move upward through the top beds of this old land surface and probably laterally across the beds near the top of the structure, the porosity features being sufficiently large to provide for gravity separation of the oil and water. The consensus is that the Oklahoma City pool did have a common water table and the contrary evidence seems to be due to unequal rates of withdrawal. The foregoing, briefly described, type of accumulation has been suggested by Thomas,⁵ Levorsen,⁶ and others in the past.

It is the writer's purpose to show the amount of Cherokee shale needed to produce the Oklahoma City oil reserve but before proceeding with the calculation, it is advisable to discuss the basis for the many assumptions used in this study.

ASSUMPTIONS

The principal assumptions required are (1) the original organic content of the source sediment, (2) the proportion of organic matter that is converted to crude oil, (3) the percentage of generated oil that is lost during migration, (4) the percentage of shale compaction, and (5) a reasonable figure for the original amount of oil in the Oklahoma City pool.

Organic content, conversion and loss due to migration.—Trask⁷ used 3 per cent for the original organic content of the source sediments for the Santa Fe Springs, California, oil field. For converting the organic

⁵ C. R. Thomas, "Flank Production of Nemaha Mountains (Granite Ridge), Kansas," *Structure of Typical American Oil Fields*, Vol. 1 (Amer. Assoc. Petrol. Geol., 1929), pp. 60-72.

⁶ A. I. Levorsen, "Relation of Oil and Gas Pools to Unconformities in the Mid-Continent Region," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), pp. 761-84.

⁷ Parker D. Trask, "Proportion of Organic Matter Converted into Oil in the Santa Fe Springs Field, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 3 (1936), pp. 245-57.

matter to oil, he suggested factors ranging from 4 to 15 per cent. His assumption that 50 per cent of the oil was lost during migration appears reasonable. Trask's assumptions, except that of 3 per cent organic matter in the original source sediment, are used as a basis for this Cherokee exercise. This study is predicated on the hypothesis that there was a local and prolific accumulation of organic matter in the Cherokee.

A mud⁸ containing 35 per cent (dry-weight basis) organic matter was found in one locality of the Black Sea. Strøm⁹ reports the finding of a mud in a Norwegian fjord with 23.4 per cent organic carbon (equivalent to 35 per cent as a minimum organic matter content or possibly 40 per cent organic matter as a maximum). The factors commonly used for the conversion of organic carbon to total organic matter are 1.7 for unreduced organic matter and 1.5 for organic matter found in subsurface lithified sediments.

On the basis of the literature it is assumed that the original Cherokee shale contained, dry weight basis, 35 per cent organic matter. Viewing the problem as a local phenomenon, this 35 per cent organic matter assumption appears conservative to the writer, particularly for the Pennsylvanian sediments which contain large amounts of organic matter.

Relative to the organic content of lithified sediments, Trask's data¹⁰ show wide variation within the same formation. For example, the organic content of the Chattanooga shale of the Seminole district, Oklahoma, was found to be as much as 7 per cent; 50 miles north of Seminole, to be 6 per cent; farther north, in scattered areas of the Burbank district, the organic content was as low as 2 per cent; and still farther north, in the Ritz-Canton district of Kansas, the organic content of the Chattanooga shale was only 1.2 per cent. In the genesis of oil, if the organic residues remaining in the lithified sediments represent, substantially, a constant proportion of the original organic matter that was preserved, then, an organic content of 2 per cent in a lithified sediment indicates that the original mud was reasonably rich in preserved organic matter and organic contents greater than this amount indicate that the sediment contained originally a very high content of preserved organic matter.

⁸ Parker D. Trask, "Organic Matter," *Recent Marine Sediments* (Amer. Assoc. Petrol. Geol., 1939), pp. 428-53.

⁹ K. M. Strøm, "Land-Locked Waters and Black Muds," *Recent Marine Sediments* (Amer. Assoc. Petrol. Geol., 1939), pp. 356-72.

¹⁰ Parker D. Trask and Harold E. Hammar, "Organic Content of Sediments," *Amer. Petrol. Inst.* (reprint), Fifteenth Annual Meeting at Dallas, Texas, November 14, 1934.

Compaction.—The next assumption concerns compaction of the source sediment. Athy,¹¹ working with clay under water, obtained a compaction of 40 per cent by subjecting the clay to a pressure of 4,000 pounds. It appears reasonable to assume that a mud or rather a "muck," high in organic matter, would compact more than 40 per cent. A 60 per cent compaction factor was chosen on the basis of the following data used in the reconstruction of an original hypothetical Cherokee mud.

TABLE I

	<i>Dry Basis</i>	
	<i>Weights Grams</i>	<i>Volumes Milliliters</i>
Organic matter of 1.0 density	35.0	35.0
Clay of 2.5 density	65.0	26.0
Totals	100.0	61.0

It is assumed that the wet "muck" had a false porosity (the suspension of clay and organic particles do not essentially touch) of 80 per cent. Thus in this original wet state the absolute volume of the clay and organic matter (61 ml.) represents 20 per cent of the total wet mud volume which is 305 ml. The composition, in terms of volume per cent, before and after 60 per cent compaction, is shown in Table II.

TABLE II

	<i>Before Compaction Percentage by Volume</i>	<i>After 60 Per Cent Compaction Percentage by Volume</i>
Organic matter	11.47	28.7
Clay	8.53	21.3
Water	80.00	50.0
Totals	100.00	100.0

The total oil reserve for the Oklahoma City pool is assumed to be 600 million barrels; the gas was not included because data on the gas reserves were not available.

Summary of assumptions.—

	<i>Percentage by Volume</i>
1. Organic content of original mud	11.47
2. Compaction factor	60.0
3. Organic content after compaction	28.7
4. Conversion factor (organic matter to oil)	4.5
5. Loss of oil due to migration to reservoir	50.0
6. Total oil in the pool, prior to production, 600 million barrels	
7. Cherokee shale wedge is represented in section as a right-angle triangle	
8. Cherokee shale thickness (basinward) is assumed to be 264 feet (0.05 mile)	

¹¹ L. F. Athy, "Density, Porosity, and Compaction of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 1 (1930), pp. 1-24.

The original organic content (11.47 per cent by volume) becomes 28.7 per cent by volume of the shale after compaction. The 600 million barrels of oil in the reservoir represents 4.5 per cent (the conversion factor) of 28.7 per cent, or approximately 1.3 per cent of the volume of the source beds after compaction, provided there was no loss during migration. As the loss due to migration is assumed to be 50 per cent, the total oil in the reservoir (600 million barrels) is equivalent to 0.65 per cent of the volume of the source beds after compaction. Therefore the volume of the source beds, after compaction, in round numbers is 3.5 cubic miles.

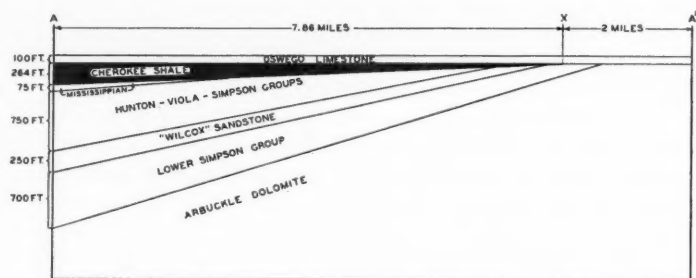


FIG. 2.—Generalized cross section (AA'), showing beds from Arbuckle limestone to Oswego limestone.

The radial extent of the Cherokee shale (Fig. 2), west of the fault, required to furnish 3.5 cubic miles of source beds, with a thickness, basinward, of 0.05 mile, now can be calculated by using the following formula.

$$\frac{h[Pi(X+R)^2] - PiR^2}{4} = Y.$$

$h = 0.05$ mile (assumed thickness of shale, basinward).

$Pi = 3.1416$ (decimal dropped in solution).

$R = 2$ miles (distance from fault to the updip limit of shale wedge, arbitrarily placed).

$Y = 3.5$ cubic miles (volume of source beds).

X = Radial extent of the Cherokee shale, to be calculated.

Approximate solution

$$(X+R)^2 = X^2 + 4X + 4 \text{ and } Pi(X+R)^2 = 3X^2 + 12X + 12;$$

$$0.05X \frac{3X^2 + 12X + 12 - PiR^2}{4} = Y; 3X^2 + 12X = 80Y;$$

completing the square by adding 12 to both sides and multiplying through by 3; $(3X+6)^2 = 240Y+36$;

$$3X = \sqrt{240Y+36} - 6, \text{ then as } Y = 3.5;$$

$$3X = \sqrt{876} - 6 \text{ and } X = 7.86 \text{ miles.}$$

DISCUSSION OF MAP (FIG. 2)

The inner semi-circle represents the updip limit of the Cherokee shale wedge, arbitrarily placed. The outer semi-circle represents the 264-foot (0.05 mile) shale isopach line, an arbitrary line but calculated to be 7.86 miles from the inner semi-circle. The areal extent, west of the fault, is 146.7 square miles.

The shale under the area of the inner semi-circle, not included in the calculation, would furnish approximately 2 per cent of the Oklahoma City oil reserve, on the assumption of a thickness of 66 feet.

There was no particular reason for placing the updip limit of the shale 2 miles west of the fault. The solution would have varied only a small amount if a "point origin" near the center of the structure and at the fault had been used.

CONCLUSIONS

On the basis of the concepts set forth herein, the distance of the migration of the oil to the Oklahoma City reservoir need not have exceeded 7.86 miles. The writer believes that the migration and the volume of the source beds (the Cherokee shale as now found) might very well be less than 7.86 miles and 3.5 cubic miles when consideration is given to the obvious physical character of the shale sediment after it had been compacted 60 per cent (Table II). At this stage the organic had not been converted to oil and it appears reasonable to assume that an organic sediment of this nature would undergo further compaction before reaching the present indurated condition of the Cherokee shale.

TANSILL FORMATION, WEST TEXAS AND SOUTHEASTERN NEW MEXICO¹

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Midland, Texas, and Carlsbad, New Mexico

ABSTRACT

This paper presents a formal definition of the Tansill formation and detailed measurement and description of the section exposed at the type locality. The typical surface section is correlated with well known subsurface sections in order that the application of the name in the subsurface may be clearly understood. In addition the relation of the Tansill limestone to the Tansill anhydrite and the relations of the Tansill formation to the Capitan limestone, and to the underlying Yates and overlying Salado formations, are briefly set forth. The Tansill formation is bounded by two important Permian horizons of West Texas and New Mexico: at the base is the familiar "top of the Yates," and at the top is the boundary between the Ochoa and Guadalupe series. These are designated TY and OG, respectively, and some significant facts about them are brought out. The Ocotillo silt member of the Tansill formation is also named and defined.

INTRODUCTION

Subsurface geologists of West Texas and southeastern New Mexico long have recognized the existence of an unnamed post-Yates pre-Salado⁴ formation, commonly more than 100 feet thick. In the recently published Part I of the West Texas-New Mexico Symposium⁵ this formation was called Tansill, and promises were made of a forthcoming formal definition. It is the purpose of the present paper to fulfill those promises without waiting for the delayed appearance of Part II of the symposium.

Lang's⁶ "Three Twins member of the Chalk Bluff formation" seems to include both the Tansill formation and the Yates sand; but, if so, the two units are described as intergradational, and the superposition of the Tansill on the Yates is not clearly recognized. His Chalk Bluff formation is essentially the "Whitehorse group"⁷ of subsurface geologists.

¹ Manuscript received, February 10, 1941.

² Argo Oil Corporation.

³ Consulting geologist.

⁴ Salado is used herein instead of the "Upper Castile" of older nomenclature. See Ronald K. DeFord and E. Russell Lloyd, "West Texas-New Mexico Symposium: Part I. Editorial Introduction," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 1 (January, 1940), p. 11. Over wide areas a basal anhydrite member of the Salado occupies the interval between the "base of the salt" and the top of the Tansill.

⁵ *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 1 (January, 1940), pp. 9, 10-11, 35, 49, 61, 135, and 139 (Fig. 3).

⁶ Walter B. Lang, "The Permian Formations of the Pecos Valley of New Mexico and Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 21, No. 7 (July, 1937), pp. 859-63, 879.

⁷ DeFord and Lloyd, *op. cit.*, pp. 8-10.

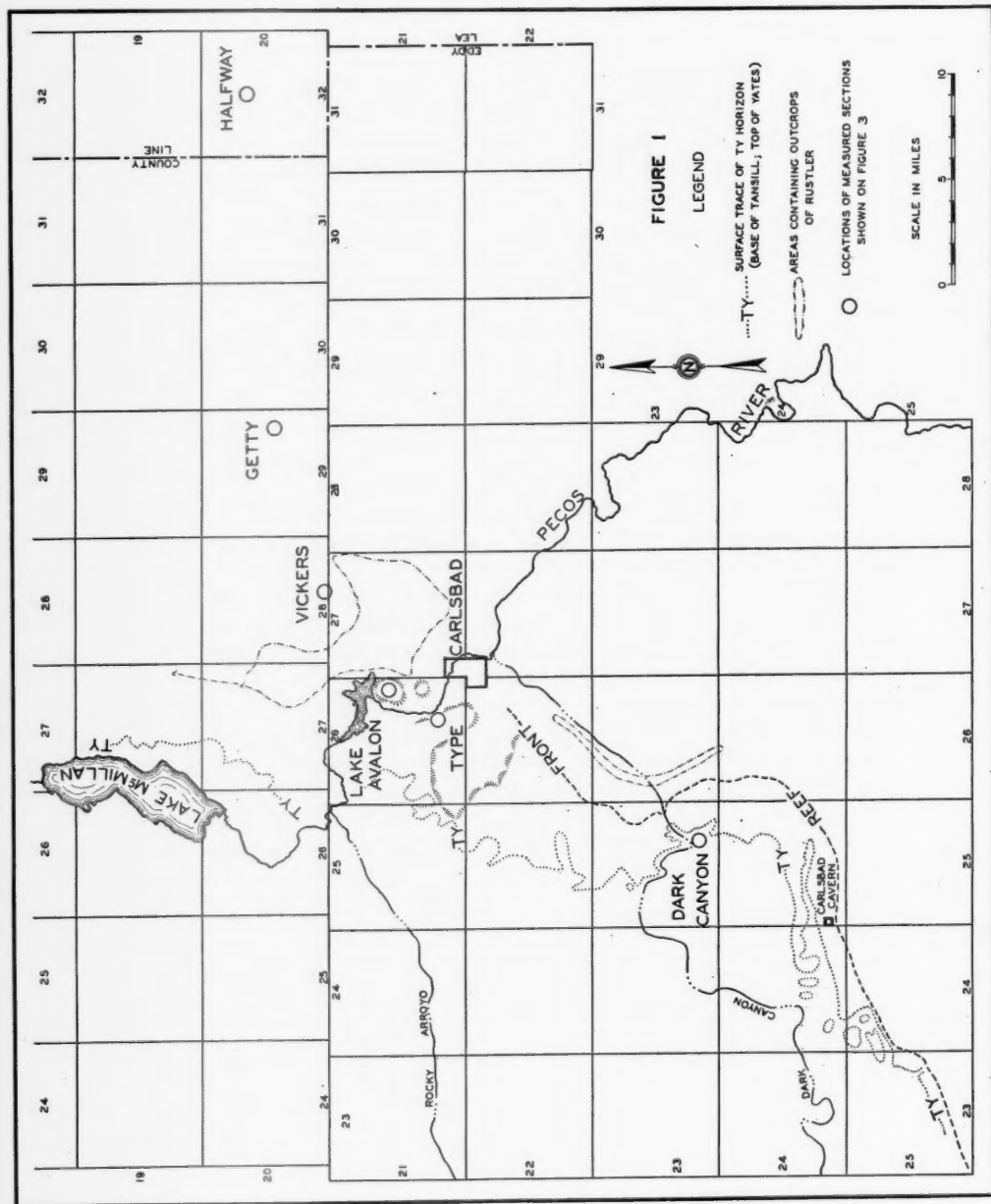


FIG. 1.—Vicinity of Carlsbad, Eddy County, New Mexico. Squares are townships, 6 miles on a side. Width of map, 55 miles. Numerals are townships south and ranges east of New Mexico Principal Meridian. Pecos River flows south.

WHAT IS A FORMATION?

A formation is a cartographic unit. In rapid surface mapping of scattered outcrops, it is commonly also a lithologic unit, which, like the Mesaverde formation, may traverse time "lines." Where plentiful subsurface data supply "the third dimension to geology,"⁸ time "lines" become time horizons, and the tendency grows to attempt to confine formations between time horizons. Formations are still the cartographic units of subsurface maps, but their lithologic unity is more apt to be neglected; for the desideratum is to trace the time horizons as widely as possible. This attempt, so far as it succeeds, is commendable, because it is a step nearer a true history of the geologic past.

Thus the Tansill formation is a body of limestone, silt, and anhydrite that forms a widespread layer of the earth's crust in southeastern New Mexico and West Texas. Limestone on the south and west grades into anhydrite on the north and east. The limestone lies around the rim of the Delaware basin. The time horizon at the top of the Tansill limestone can be traced basinward where it becomes the top of the Capitan limestone and forms the front of a great barrier reef dipping steeply downward 1,500 feet into the basin—where it becomes in turn the top of the Delaware Mountain group. This horizon can also be traced, somewhat less definitely, "lagoonward," away from the basin, where it becomes the top of the Tansill anhydrite and is in most places somewhat below the horizon known as the "base of the salt." The horizon that forms the top of the Tansill formation is the boundary between the Guadalupe and Ochoa series. In this region the Tansill is the top formation of the "Whitehorse group" of the Guadalupe series of the Permian system.

The time horizon at the base of the Tansill formation is the key horizon most widely used in mapping the subsurface structure of the Permian in West Texas and New Mexico; for it is the well known "top of the Yates sand." Basinward it plunges into the massive reef rock of the Capitan limestone, wherein it becomes indistinguishable.

In this paper the top of the Tansill is called "the OG horizon," or simply OG (from the Ochoa and Guadalupe series). The base of the Tansill is called "the TY horizon," or simply TY (from Tansill and Yates). TY is easy to remember, since it can also stand for the widely publicized "top of the Yates."

TANSILL TYPE LOCALITY

Because it is easy to make mistakes in correlation and difficult to avoid them, it is necessary in defining a formation to refer to its typical

⁸ Hugh D. Miser, "Our Petroleum Supply," *Jour. Washington Acad. Sci.*, Vol. 29, No. 3 (March 15, 1939), p. 103.

development at a single well described place.⁹ The easily accessible type locality¹⁰ of the Tansill formation is on the Carlsbad-Artesia Highway (U. S. 285) 3.7 miles from the Eddy County Courthouse in Carlsbad. It is in the W. $\frac{1}{4}$ of Sec. 26, T. 21 S., R. 26 E., of the New Mexico Principal Meridian, in Eddy County, New Mexico.

The Tansill power dam at Carlsbad backs up the water of the Pecos River to form a narrow lake 3 miles long. The head of this lake is near Carlsbad spring, where the irrigation-ditch aqueduct crosses the Pecos River. Here in the river is a small riffle; then standing water again, extending $\frac{1}{2}$ mile upstream to the Tansill type locality (Fig. 2).



FIG. 2.—Tansill type locality. Dip is about 12° toward observer. Dip slope on sky line formed by unit XIII, Table I. Unit XII exposed in road-cut. Average distance between white posts along highway is 10 feet. Ledge beneath road is unit XI. Ocotillo member covered by talus. Pecos River in foreground.

The road-cut exposes the upper, clastic part of the formation. The lower part is well exposed in the C.C.C. rock quarries on both sides of the small canyon 0.2 mile northwest.

The measured section is summarized in Table I.

⁹ *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 7 (July, 1933), p. 854. *Ibid.*, Vol. 23, No. 7 (July, 1939), p. 1079.

¹⁰ Road log, "West Texas Geological Society Fall Field Trip, Eddy County, New Mexico, September 28-29, 1940," pp. 6-7, Stop 4.

TABLE I
MEASURED SECTION OF TANSILL FORMATION AT TYPE LOCALITY

	Thickness (Feet)
XIII. Magnesian limestone	5.0
XII. Silt and marl	2.5
XI. Yellowish magnesian limestone	17.2
X. Silt	7.0
IX. Buff-gray magnesian limestone	1.5
VIII. Sand and marl	5.0
VII. Magnesian limestone	4.5
VI. White chalky marl	0.3
V. Buff magnesian limestone	13.0
IV. Brown magnesian limestone	55.5
III. Silt and fine sand	2.0
II. Gray, silty, magnesian limestone	1.0
I. Brown magnesian limestone	9.0
	123.5
TV.	
Light-colored fine sand	0.5

The same section is described in Table II.

Structure.—At the type locality the strike is northeasterly, and the beds dip southeastward. Dips ranging from 9° to 14° were measured. The average is about 12° , S. 36° E.

Fossils.—The type section of the Tansill formation contains no recognizable fossils. The upper part has many beds of dense limestone, some of it lithographic. Much of this may have been deposited mechanically as calcareous mud to be compacted later into dense limestone. The lower 50 feet of section at the type locality (units 1-33, Table II) contain considerable organic matter. The openings in some beds of limestone (unit 26, Table II, and some underlying strata) seem to be casts formed by the dissolving out of fossil shell fragments.

The gradation of the thin-bedded Tansill into the massive Capitan is well exposed in the canyon walls near the mouth of Dark Canyon (T. 23 S., R. 25 E., Fig. 1). As they approach the Capitan the strata of the Tansill become thicker and fossils appear. Gastropods are noteworthy plentiful. The Capitan itself bears the youngest part of the Guadalupian fauna.¹¹ Fusulinids, crinoids, algae, and other forms are found at the very top of the Capitan; that is, clear up to OG.

Ocotillo member.—We propose that the section comprising units VIII, IX, and X of Table I and units 42 to 51, inclusive, of Table II be called the Ocotillo silt member of the Tansill formation.

The Tansill type locality is on the east flank of an elongate dome that forms a prominent topographic feature northwest of Carlsbad. The structure was called the Carlsbad dome by some early petroleum

¹¹ George H. Girty, "The Guadalupian Fauna," *U. S. Geol. Survey Prof. Paper* 58 (1908).

TABLE II
DETAILED DESCRIPTION OF TANSILL TYPE SECTION AND INSOLUBLE RESIDUE*

No.	Thickness in Feet and Description of Beds	Insoluble in HCl	
		%	Description
XIII	5.0 MAGNESIAN LIMESTONE		
66	3.0 gray to brownish gray, dense, flaggy ls. that weathers into $\frac{1}{4}$ - to 1-inch beds; scattered porosity	8	2% light silt; 6% gray clay
65	2.0 buff dense ls.; 6-inch to 12-inch beds; scattered porosity	2	$\frac{1}{2}$ % light silt; $1\frac{1}{2}$ % yellowish brown clay
XII	2.5 SILT AND MARL		
64	0.7 light silty marl	27	5%—light silt; 22%+ light clay
63	0.7 greenish yellow, calcareous, micaceous silt (0.03–0.05 mm.)	57	47%—silt; 10%+ clay
62	0.4 light calcareous, micaceous silt	33	23% silt; 10% clay
61	0.1 gray, dense ls.	11	5% gray silt; 6% clay
60	0.3 greenish gray, calcareous, micaceous silt	21	16%—silt; 5%+ clay
59	0.3 dense, greenish gray, somewhat porous ls.	15	3%+silt; 12%—light clay
XI	17.2 YELLOWISH MAGNESIAN LIMESTONE		
58	0.8 buff-yellow, crystalline, porous ls.	3	$1\frac{1}{2}$ % light silt; $1\frac{1}{2}$ % dark yellow clay
57	2.0 yellow, highly crystalline and re-crystallized, very porous ls. grading downward into less porous ls. At bottom is light gray ls. with scattered porosity and calcite crystals filling or partly filling pores	4	1% light silt; 3% tan and red clay
56	1.0 buff ls., less porous, less calcite	3	$\frac{1}{2}$ % light silt; $2\frac{1}{2}$ % tan clay
55	1.9 yellow, highly crystalline and re-crystallized, very porous ls. grading downward into less porous ls. Near bottom is buff ls. in which calcite crystals form a texture like graphic granite	2	$\frac{1}{2}$ % light silt; $1\frac{1}{2}$ % orange to tan clay
54	4.0 gray-buff, dense, slightly porous ls. in 3- to 12-inch beds; trace of calcite crystals	4	1%—light silt; 3%+ grayish tan clay
53	4.5 yellow-buff, dense ls. in 3- to 18-inch beds; some calcite crystals; gray dense ls. near base	5	1% light silt; 4% yellow clay
52	3.0 yellow, dense ls. in 6- to 12-inch beds; some calcite crystals	4	1%—light silt; 3%+ yellow clay
X	7.0 SILT		
51	1.0 light gray, calcareous, slightly micaceous silt, with tiny lenses of green shale	43	38% light silt; 5% light clay
50	1.0 light, chalky, slightly micaceous silt, with tiny lenses of green shale that swells and flakes in water	61	50%+ light silt; 5–10% light clay
49	3.0 yellowish, very slightly micaceous silt (swells somewhat in water)	70	65%+light (slightly yellowish) silt; 5%—clay
48	1.0 light gray, calcareous, slightly micaceous silt (swells readily in water)	48	43%+light silt; 5%—clay, slight brownish tinge
47	0.5 light gray, calcareous, slightly micaceous silt (harder and more calcareous than No. 48, almost a marl; does not swell in water)	38	33%+light silt; 5%—clay, slight brownish tinge
46	0.5 covered		

TANSILL FORMATION, TEXAS AND NEW MEXICO 1719

TABLE II—Continued

No.	Thickness in Feet and Description of Beds	Insoluble in HCl	
		%	Description
IX 45	1.5 BUFF-GRAY MAGNESIAN LIMESTONE 1.5 buff-gray, very dense ls.; trace of porosity	7	4% light silt; 3% yellow clay
VIII 44	5.0 SAND AND MARL 1.0 white marl	34	30% light gray silt; 4% clay
43	1.7 light gray, very fine, calcareous, micaceous sand (0.05 mm. +)	67	62% + light fine sand and silt; 5% - light (slightly brownish) clay
42 VII	2.3 covered 4.5 MAGNESIAN LIMESTONE		
41	1.7 greenish gray (reddish mottled), dense, somewhat crystalline ls.; trace of porosity	3	1% - light silt; 1% + yellow clay; little crystals of hematite pseudomorphic after pyrite
40	1.0 yellow, porous, crystalline ls.; much recrystallized (calcite in bands); less porous downward	2	1% light silt; 1% yellow clay
39	1.8 gray-buff, dense ls.; trace of porosity	2	1% light silt; 1% yellow clay
VI 38	0.3 WHITE CHALKY MARL 0.3 white chalky marl	11	11% light clay, practically no silt
V 37	13.0 BUFF MAGNESIAN LIMESTONE 13.0 dense, bedded ls.: bluish gray ls. bed at top;	3	1% silt; 2% gray clay; trace of mica
	rest is buff; trace of porosity which in upper part contains organic matter	1	1% - silt; 1% + buff clay; trace of mica
IV 36	54.5 BROWN MAGNESIAN LIMESTONE 34.0 brown to dark brown, bedded ls.: 0.8 buff, dense, laminated ls.; a ledge-maker	1	1% silt; 1% buff-gray clay
35	2.5 buff, dense ls.		
34	14.0 brown, dense ls.; some beds more lithographic, some less so	1	trace of silt; 1% - brownish gray clay; trace of mica
33	3.5 dark brown porous ls. with organic matter in pores	1	1% light silt; 1% brown clay; somewhat organic; trace of mica
32	5.5 dark brown porous ls. with organic matter in pores	1	trace of light silt; 1% dark brown clay (which is largely organic)
31	0.5 dark brown, somewhat laminated ls.; somewhat porous with organic matter in pores	1	1% - brown silt with trace of mica; trace of brown clay (which is largely organic)
30	0.2 dark brown, dense, thin-bedded ls.	2	1% brown silt with trace of mica, 1% brownish gray, somewhat organic clay

TABLE II—Continued

No.	Thickness in Feet and Description of Beds	Insoluble in HCl	
		%	Description
29	5.5 brown to gray ls.; somewhat porous with organic matter in pores	1	1% brown silt with trace of mica; trace of brown clay; many pieces of black asphaltic material
28	1.0 single bed of brown ls.; somewhat porous with organic matter in pores	$\frac{1}{2}$	trace of light silt; $\frac{1}{2}$ %—reddish brown, largely organic clay
27	0.5 single bed of brown ls.; lighter brown than No. 28	1	trace of light silt; 1%—brown clay; considerable oily residue
26	12.5 brown ls. in-beds 6–18 inches thick: 2.0 light brown, crystalline, porous ls.; some openings seem to be casts of fossils	1	trace of light silt; 1%—dark brown, somewhat organic clay
25	1.0 brown, dense ls.; trace of porosity, trace of organic matter in pores	1	$\frac{1}{2}$ % light silt; $\frac{1}{2}$ % dark brown organic clay; little oil on beaker
24	1.2 buff porous ls.	$\frac{1}{2}$	trace of light silt; $\frac{1}{2}$ %—dark brown organic clay
23	3.0 brown, crystalline, porous ls.	1	trace of light silt; 1%—dark brown organic clay; little oil on beaker
22	2.0 brown, crystalline, somewhat porous ls.; somewhat darker brown than No. 23	$\frac{1}{2}$	trace of light silt; $\frac{1}{2}$ %—dark brown (almost black), largely organic clay; much oil on beaker
21	3.3 light brown to brown ls., some of it porous	1	trace of light silt; 1% dark brown and black, largely organic clay
	No. 21 has light marly streaks along its bedding planes	5	3% light silt; 2% brown clay
20	5.0 brown ls.: this is prominent 5-foot ledge-maker that commonly marks position of underlying "Top of Yates" horizon: 3.0 brown dense ls., trace of porosity	$\frac{1}{2}$	trace of light silt; $\frac{1}{2}$ %—dark brown, largely organic clay; oil on beaker
19	1.0 brown, dense, laminated ls.	$\frac{1}{2}$	slight trace of silt; $\frac{1}{2}$ % brown organic clay
18	1.0 light brown ls.	$\frac{1}{2}$	trace of silt; $\frac{1}{2}$ % dark brown, largely organic clay; oil on beaker
17	4.0 brown ls.: 0.1 brown ls.		
16	0.7 light brown, crystalline, porous ls.	3	1 $\frac{1}{2}$ % silt; 1 $\frac{1}{2}$ % brown, somewhat organic clay

TANSILL FORMATION, TEXAS AND NEW MEXICO 1721

TABLE II—Continued

No.	Thickness in Feet and Description of Beds	Insoluble in HCl	
		%	Description
15	1.0 brown ls.		
14	1.2 brown ls. locally light marl occurs between No. 14 and No. 13	9	5% silt (0.05 mm.+) with trace of mica; 4% gray clay
13	1.0 brown ls.		
III	2.0 SILT AND FINE SAND		
12	0.3 light micaceous silt or fine sand (0.05 mm.)	59	54% fine sand (0.05-0.1 mm.); 5% gray clay; mica
11	0.2 light, micaceous, silty ls. or calcareous silt	38	35% silt to fine sand; 3% gray clay
10	0.8 light, micaceous, fine sand	43	40%+ fine sand; 3% gray clay; trace of mica
9	0.7 light, very calcareous, micaceous silt and sand	40	38% silt to fine sand 2% gray clay; trace of mica
II	1.0 GRAY, SILTY, MAGNESIAN LIMESTONE		
8	0.3 gray porous ls.	17	15% light silt; 2% gray clay; trace of mica
7	0.1 gray micaceous silt	35	33% light silt and fine sand; 2% light clay; trace of mica
6	0.3 gray to buff, somewhat laminated ls.	24	22% light silt and fine sand; 2% light gray clay; trace of mica
5	0.3 light brown, dense ls. with big pore spaces, oölitic at top	8	7% light silt; 1% gray clay; trace of mica
I	9.0 BROWN MAGNESIAN LIMESTONE		
4	2.0 grayish brown dense ls.; at top is bed of algal(?) ls. 0.2-0.4 feet thick, which is bounded underneath by pressure sutures	1	1% light silt; 1% brown, somewhat organic clay
3	2.0 grayish brown, crystalline porous ls.	3	2% gray silt; 1% brown, largely organic clay
2	2.0 grayish brown porous ls.	5	3% light silt (0.04 mm.); 2% grayish brown clay containing organic matter
1	3.0 grayish brown, crystalline to dense ls. in 1/2-inch bands; some porous, some non-porous	3	1% light silt (0.04 mm.); 2% dark brown clay containing organic matter
-----TOP OF YATES-----			
	0.5 LIGHT-COLORED FINE SAND	22	20% fine sand (0.05-0.1 mm.); 2% buff clay; trace of mica

* The following abbreviations are used.

Ls. = limestone: all the limestone, including cementing material, is magnesian limestone, excepting a few sporadic calcite crystals formed by surface weathering.

Sand = grains of silica larger than 0.05 mm. in diameter; the sand is angular and very fine—0.05 to 0.1 mm.

Silt = grains 0.0005 to 0.05 mm.; the silt is mostly in the upper part of the range—0.01 to 0.05 mm.

Light = light-colored.

Oil on beaker = oily scum that floated on liquid in beaker while sample was being dissolved in HCl to obtain insoluble residue.

geologists and the Tracy dome by others on account of a deep test well, the Ohio Oil Company's Tracy No. 1, drilled thereon. The prominent topographic feature formed by the dome seems on inquiry among local residents to lack a name. Lang,¹² however, called this feature the "Ocotillo Hills," whence the name of the Ocotillo member.

The 2½-foot silt and marl member near the top of the Tansill (unit XII, Table I; units 59-64, Table II) is not a part of the Ocotillo member but is separated from it by 17 feet of yellowish limestone. The thin silts of unit XII are not identifiable in the cuttings from every well, though they are found in some wells. The Ocotillo member, on the contrary, can be traced consistently for more than 100 miles.

False Yates.—The 3-foot clastic section near the base of the Tansill (units II and III, Table I; units 5-12, Table II) seems to be a "stray sand" above the Yates. It is represented elsewhere by marly limestone.

TANSILL TIME

The time interval between TY and OG is recorded by the Tansill formation. At the type locality, for example, Tansill time is represented by beds of rock and by bedding planes. The proportion belonging to each is an open question. Deposition was continual, not continuous. The statement that more time is represented by bedding planes than is represented by rock is no more patently absurd than its opposite. The time represented by bedding planes is here and there shown concretely by the addition of a marl bed between two beds of limestone (as within unit 21 and between units 13 and 14, Table II).

The type section of the Tansill contains about 250 "horizons of interruption," not counting laminations or gradational contacts. The average bed, therefore, is a 6-inch stratum of limestone bounded by two sharply defined bedding planes that weather out as little benches. The following averages may be speculatively interesting, even if they apply not at all to Tansill time and the Tansill formation. There is a fairly "complete" representation of the Permian system in this region comprising about 10,000 feet of Permian rocks. An estimated length of Permian time is 40 million years.¹³ The thickness of the Tansill is about 1¼ per cent of the stated total. Multiplying this figure mechanically by 40 million gives 500,000 years; and dividing 500,000 by 250 yields an average figure of 2,000 years, supposedly represented by a

¹² Walter B. Lang, "A Reconnaissance and Elevation Map of Southeastern New Mexico," *U. S. Geol. Survey* (1937), scale 3 miles to 1 inch.

¹³ Charles Schuchert and Carl O. Dunbar, *A Textbook of Geology. Part II. Historical Geology*, 3d ed. John Wiley and Sons, New York (1933), p. 80.

6-inch bed of limestone and one of its associated horizons of non-deposition.

As previously stated, Tansill limestone grades into Tansill anhydrite. What were the time relations of limestone and anhydrite deposition? In Rocky Arroyo a thick limestone section, somewhat older than Tansill, grades in a short distance into a thicker section of gypsum. One geologist who studied this gradation said that the limestone beds seem to open "like the leaves of a book." There is certainly evidence that some of the gypsum beds are represented by bedding planes in the limestone—and *vice versa*. It is a provocative question, then, how much of the Tansill anhydrite of subsurface sections at the northeast is represented by bedding planes at the type locality and how much by limestone.

CORRELATIONS

Figure 3 traces the Tansill formation by correlation from the type locality eastward into the subsurface as far as the Halfway pool in western Lea County, New Mexico. This will serve as an illustrative application of the names Tansill and Ocotillo to a familiar subsurface section. It is equally easy to trace OG and TY from Halfway southward to Jal in the southeast corner of New Mexico, and thence southward into West Texas through Winkler and Ward counties. Correlations from well to well along this narrow trend from Halfway to Pecos County, Texas, have been made many times by many geologists in the course of their daily work. Different geologists may use different horizons of the Tansill-Yates section, but, except for minor, locally compensating discrepancies, they are in agreement as to the correlations.

The surface and subsurface sections in Figure 3 are assembled on OG as a datum plane. OG is not exposed for inspection at the type locality of the Tansill formation; therefore the type section is not quite complete—about 5 feet of beds are missing from the top. The term Tansill formation, like most of the names in Permian basin nomenclature, can not be comprehended properly without considering the subsurface sections as well as the surface outcrops.

Dark Canyon.—At the left side of Figure 3 is shown a measured section that crops out in and near the SW. $\frac{1}{4}$ of Sec. 27, T. 23 S., R. 25 E., about 14 miles south-southwest of the Tansill type locality. It is exposed in Dark and Moseley canyons, about 2 miles upstream from the mouth of Dark Canyon.

Avalon.—The first subsurface section shown in Figure 3 is $2\frac{1}{2}$ miles northeast of the Tansill type locality. It is the log of Neil H. Wills'

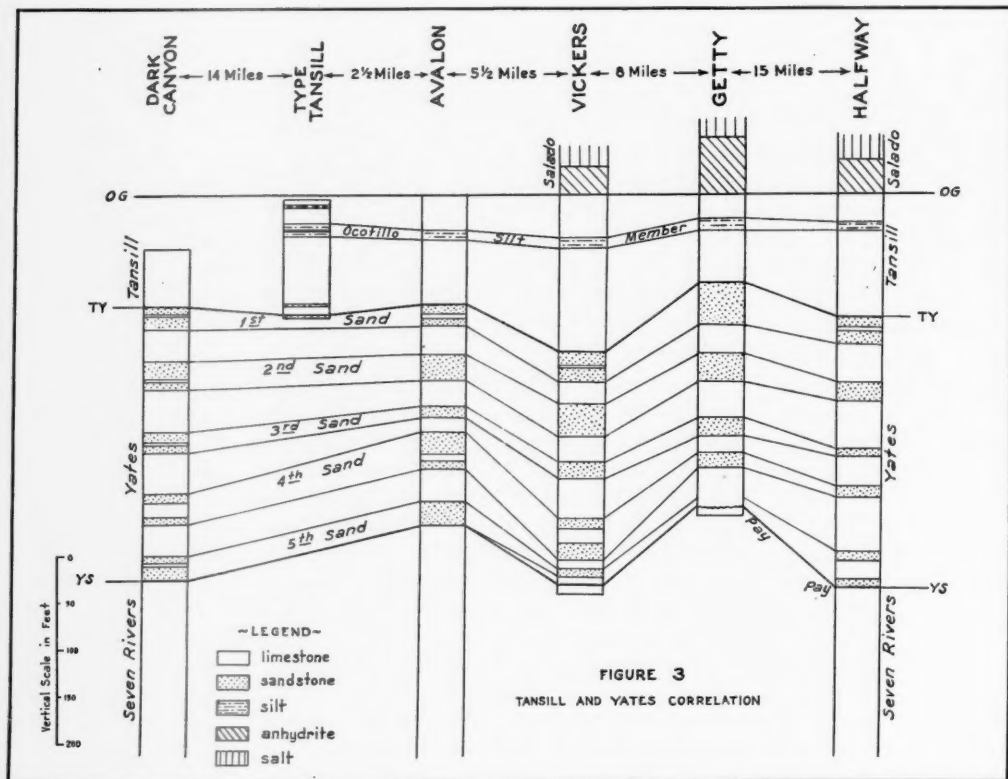


FIG. 3.—Surface and subsurface sections near Carlsbad, New Mexico. Location of sections shown in Figure 1.

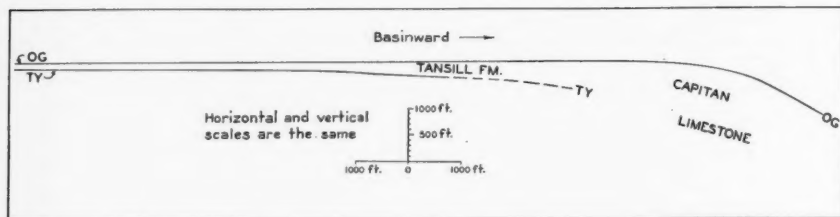


FIG. 4.—Relation of top of Yates (TY) to top of Tansill (OG). Vertical scale not exaggerated. Width of figure about 3 miles.

Byall No. 1, drilled on the Avalon dome, in the NW. $\frac{1}{4}$ of Sec. 13, T. 21 S., R. 26 E. This well starts practically at the top of the Tansill.

Vickers.—The next section is $5\frac{1}{2}$ miles northeast of the Avalon dome and was drilled in Flynn, Welch, and Yates' Vickers No. 1 in the SW. $\frac{1}{4}$ of Sec. 34, T. 20 S., R. 28 E. Salt and anhydrite members of the Salado are present there, and OG is established by the contact of the basal anhydrite member on the underlying Tansill limestone.

Getty.—The Getty pool in Secs. 13, 23, 24, and 25, T. 20 S., R. 29 E., is 8 miles east-northeast of the Vickers well. A typical Getty section is shown in Figure 3.

Halfway.—The Halfway pool is 15 miles east of the Getty pool and 30 miles east-northeast of the Tansill type locality. A subsurface section at Halfway is shown on the right side of Figure 3.

In these unweathered subsurface sections the limestones of the Tansill are commonly anhydritic, and thin beds of anhydrite are present near the top of the formation, though not shown in Figure 3.

The Ocotillo silt member is gray in places, red in others. In places it contains shaly and sandy beds. A recently drilled wildcat well, Neil H. Wills' Hale No. 1 in the SW. $\frac{1}{4}$ of Sec. 12, T. 20 S., R. 30 E., obtained a flow of gas from the Ocotillo member that gauged 6 million cubic feet per day.

The limestone at the base of the Tansill is organic, and in many wells is dark brown and oil-stained.

THICKNESSES

Most of the sections shown in Figure 3 occur on the tops or flanks of local domes and are therefore thin. Thickening of the Tansill formation off structure is illustrated by the Vickers section, which has 165 feet of Tansill as against 95 feet in the Getty section and 115 feet on the Avalon dome.

Tracing beds and measuring sections along a stratigraphic strike, one finds that the average thickness of the Tansill formation remains constant. OG and TY diverge in the synclines and converge over anticlines to give the local variations in thickness illustrated in Figure 3.

When the geologist follows the beds toward the Delaware basin, at right angles to the stratigraphic strike, he observes a different phenomenon. Generally, each older horizon steepens its basinward dip before the next younger horizon, and each younger horizon extends as a shelf farther basinward than the next older, before beginning its plunge into the Delaware basin. The result is the basinward thickening of almost every member.

The phenomenon is illustrated in Figure 4, which is drawn in true

scale to show the relation between TY and OG. The parallel extension of TY and OG toward the basin, succeeded by the abrupt divergence of TY, due to downward steepening not yet shared by OG, can be observed at several places; for example, a few miles west of Carlsbad in the anticlinal ridge that extends from the southeast corner of T. 21 S., R. 25 E., southeastward to the middle of T. 22 S., R. 26 E., and also in the outcrops exposed by Dark Canyon drainage in the southwestern portion of T. 23 S., R. 25 E.

As a result of this divergence between TY and OG, the Tansill formation, normally 100-150 feet thick, so thickens at the edge of the basin that it occupies an interval of more than 300 feet before it grades into the massive reef rock of the Capitan limestone.

The Tansill limestone of the trend illustrated in Figure 2 is thin-bedded: 18 inches is probably the maximum thickness of any one bed, and the average is probably less than 6 inches. As the Tansill grades into the Capitan, not only do individual beds thicken on account of the aforedescribed divergence of older bedding planes from the younger, but also the number of bedding planes decreases. The thin-bedded limestone grades into massive-bedded and the massive-bedded into almost unbedded Capitan. It follows that many of the bedding planes of the type Tansill are represented by rock in the massive Capitan. The Capitan itself is not wholly lacking in bedding-plane diastems.

AREAL GEOLOGY

The approximate areal distribution of the Tansill outcrops in Eddy County, New Mexico, has been printed elsewhere¹⁴ and is summarized in Figure 1. The trace of the intersection of TY with the surface of the ground is shown as it was determined by reconnaissance mapping. Near Lake McMillan, Wills and Riggs mapped it with a plane table. The Tansill outcrop occupies the area between the surface trace of TY and the reef front, excepting certain small inliers of Yates that crop out here and there but are not shown on the map.

Southwest of Carlsbad the beds rise toward the high Guadalupe Mountains, where erosion has carved the topography deeply into beds older than Tansill. Thus, as the surface trace of TY extends southwestward toward the Texas line, it approaches closer and closer to the reef front; and consequently the outcrop of Tansill narrows to a thin strip perched along the top of the reef escarpment.

¹⁴ Ronald K. DeFord, Neil H. Wills, and Geo. D. Riggs, "Road Map, Fall Field Trip, West Texas Geological Society, September 28-29, 1940," in pocket at back of road log. The road log is out of print, but the map is still obtainable from the West Texas Geological Society, Midland, Texas.

Conversely, as the surface trace of TY extends northeastward toward Carlsbad, it recedes farther and farther from the reef front, and the Tansill outcrop correspondingly widens. The reef front descends northeastward so that less and less of it is exposed above the alluvium; 3 miles southwest of Carlsbad it plunges completely underground. Between that point and the Pecos River the Tansill outcrop lies between the surface trace of TY and a Tansill-alluvium contact that is shown on Figure 1 by hachures. Just east of the Pecos River, between Carlsbad and Lake Avalon, are two hachured hills of Tansill limestone, these being the farthest east outcrops of the typical thin-bedded limestone section.

East of Lake McMillan, Tansill anhydrite (cropping out as gypsum) occupies much of the surface between the trace of TY and the roughly sketched outcrop of the Rustler formation.

OCHOA-GUADALUPE UNCONFORMITY

Table III summarizes representative vertical sections in the vicinity of Carlsbad. The X's indicate missing formations.

TABLE III

	DELAWARE BASIN (South of Carlsbad)	SUBSURFACE (Northeast of Carlsbad)		SURFACE (Southwest of Carlsbad)	
		Reef	Behind Reef		
	RUSTLER SALADO CASTILE	RUSTLER SALADO CASTILE (In part)	RUSTLER SALADO XXXXXX	RUSTLER XXXXXX XXXXXX	
—OG—	DELAWARE MOUNTAIN	CAPITAN	TANSILL	TANSILL	—OG—
			YATES Pre-Yates formations	YATES Pre-Yates formations	—TY—

The Castile laps against the Capitan reef front, and "behind" the reef, in the subsurface, the Salado rests directly on the Tansill.

The top of the Tansill is the same horizon as the top of the Capitan.

The Ochoa-Guadalupe contact, OG, coincides with the Castile-Delaware Mountain contact, with the Castile-Capitan contact, and with the Salado-Tansill contact. Between the Salado and Tansill, therefore, is a disconformity representing the absence of the Castile formation.

This is a disconformity; there is no evidence, so far, of discordance in dip.

The Salado-Tansill contact is found in the subsurface east of Carlsbad. The basal anhydrite member of the Salado that rests on the Tansill is partly red, owing to inclusions of red clay. In extending westward toward the longitude of Carlsbad, the Rustler formation overlaps the Salado and at the outcrop appears to rest on the Tansill. In most places, however, a narrow soil-filled valley intervenes, and the complete absence of Salado is hard to prove.

At one place¹⁵ 6 miles west of Carlsbad an exposure of a gypsum-Tansill contact is preserved. The gypsum may be Salado or may be Rustler. The surface of the Tansill limestone at the contact is somewhat rough and weathered. Inasmuch as subsurface samples from the top of the Tansill appear fresh and unweathered, the weathering here is probably recent.

ACKNOWLEDGMENT

Neil H. Wills is our co-worker in the stratigraphy of Eddy County, New Mexico,¹⁶ and the co-author of our ideas. As this particular paper deals mainly with Tansill outcrops that were measured by us, we have assumed the authorship of this part of the work.

John J. Hill assisted in measuring the type section of the Tansill formation.

¹⁵ Near the common corner of Secs. 5, 6, 7, and 8, T. 22 S., R. 26 E. This is Stop 7, p. 8, of the road log, *op. cit.*

¹⁶ Ronald K. DeFord, Geo. D. Riggs, and Neil H. Wills, "Surface and Subsurface Formations, Eddy County, New Mexico" (abstract), *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22, No. 12 (December, 1938), pp. 1706-07.

GEOLOGY OF SOUTHERN PART OF LA BARGE REGION, LINCOLN COUNTY, WYOMING¹

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ABSTRACT

In general, the area consists of a northward-trending ridge, bounded on the west by a valley and on the east by a gently rolling basin. The dominant structural feature is the northward-trending ridge. The Darby thrust cuts the eastern flank of the ridge; the extreme northern end of the ridge is cut by a west-striking tear and two minor high-angle westward-dipping thrusts or reverse faults. In the eastern part of the area there is a secondary thrust which was detected by well data.

INTRODUCTION

The area described in this report consists of approximately 42 square miles in Lincoln County, Wyoming, about 50 miles north of Kemmerer and 4 miles west of La Barge, in T. 26 N., Rs. 113 and 114 W. (Fig. 1). The southern part of the area is traversed by the graded La Barge road, which parallels La Barge Creek, and many secondary roads. The eastern part can be reached by the graded road from La Barge to Calpet, the foothills of the central part by wagon roads, and the western part by wagon trails. The whole of La Barge Ridge, which is in the northwestern part of the area, is without roads and trails and is too rough for travel except on foot.

The geological work was undertaken for the purposes of (1) obtaining an accurate geologic map of the area and (2) description and interpretation of the stratigraphy and structural geology.

The field work was begun on July 1, 1939, and was completed on September 15, 1939. Stratigraphic sections were measured normal to strike and downdip, with the aid of the Brunton compass and a steel tape. A geologic map on the scale of 1 inch = 1,000 feet was made by the use of the plane table and telescopic alidade. The triangulation method of geologic mapping was used.

No previous detailed geological investigations of the area have been published. Schultz³ mapped a much larger area including the one mapped by the writer, but made no attempt to differentiate the Paleozoic rocks in La Barge Ridge.

The writer wishes to express his thanks to S. H. Knight, chairman

¹ Thesis submitted to the department of geology and the committee on graduate study at the University of Wyoming, in partial fulfillment of the requirements for the degree of Master of Arts, Laramie, Wyoming, 1940. Manuscript received, March 14, 1941.

² Home address, 1028 Sixth Street, Rock Springs, Wyoming.

³ A. R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *U. S. Geol. Survey Bull.* 543 (1914). 136 pp.

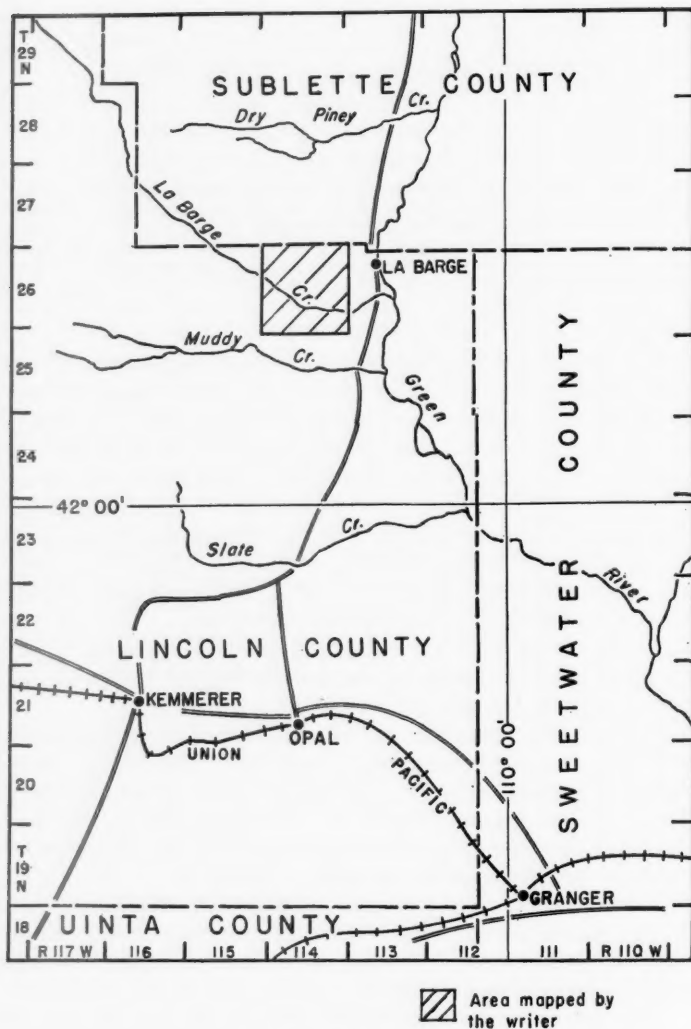


FIG. 1.—Index map.

of the geology department, who made possible the completion of this report through the facilities of the geology department of the University of Wyoming. The assistance of R. H. Beckwith, associate professor, in both the preparation of the manuscript and drafting pro-

cedure is greatly appreciated. The writer is also indebted to George R. Veronda for his valuable assistance in the field. Thanks are due also to the ranchers and oil operators in the area, whose hospitality and information greatly facilitated the completion of the field work. Stratigraphic studies were made, in the general area, in conjunction with Robert J. Minton.

TOPOGRAPHY AND DRAINAGE

La Barge Ridge is a northward-trending ridge occupying the northwestern part of the area. The western flank of the ridge drops off steeply into a valley filled with Tertiary sediments. The eastern flank of the ridge is much steeper, and in some places nearly vertical. At the north end of the area the crest of the ridge attains an elevation of 8,200 feet and gradually decreases in elevation toward the south to 7,200 feet. At the extreme southern part, La Barge Ridge disappears under the Tertiary sediments, which rise to an elevation of 7,400 feet. On the east is a gently rolling basin whose average elevation is 6,800 feet. Within the eastern half of the area, there are long, narrow ridges which rise 200 feet above the floor of the basin and slope gently east.

The major part of the area is drained by La Barge Creek, a tributary of the Green River. The northwestern slope of La Barge Ridge drains southwest into La Barge Creek, which flows southeast through a V-shaped cut in the Paleozoic rocks of La Barge Ridge. The southwestern part of the area is drained by ephemeral tributaries of La Barge Creek. The northeastern part drains into a steep-walled water course flowing directly to Green River.

STRATIGRAPHY

The thicknesses and lithologies given in the following table and discussion were obtained by measurements of stratigraphic sections in the La Barge Ridge area. The work was done by the writer and Robert J. Minton, who was at the time preparing to map the northern part of La Barge Ridge. As the same stratigraphic units are present in all parts of the ridge, the study of the stratigraphy was carried out in coöperation. Stratigraphic sections were measured with the aid of the Brunton compass and steel tape in traverses normal to strike.

CAMBRIAN ROCKS

Death Canyon limestone.—The Death Canyon is commonly included in the Gros Ventre formation as a member. Because of its distinct lithologic character and easy separation, the limestone was mapped as a separate unit. It overlies Cretaceous sediments with fault

contact, is conformably overlain in some places by the Gros Ventre, and in others is unconformably overlain by the Almy formation of Tertiary age. The Death Canyon is blue to dark gray finely crystalline

TABLE I
GEOLOGIC FORMATIONS IN LA BARGE RIDGE AREA

Age	Unit Mapped	Thickness (Feet)	Characteristics
Quaternary		0-75(?)	Floodplain gravels and sand
Tertiary	Green River	700	Light gray and tan thin-bedded sandstones, black fossiliferous paper shales, and medium-brown blocky sandstones
	Knight formation	300	Red and yellow sandy clays and variegated shales with some brown sandstones
	~Unconformity~ Almy formation	600	Red and white conglomerates, red shales and sandy clays, and red and white sandstones
	~Unconformity~		
Cretaceous	Adaville formation	1,000	White and buff sandstone, brown blocky cross-bedded sandstones, thin gray shales and sandy shales, and coal seams
	Hilliard formation	4,200	Light to dark gray sandy shales with some clays and thin-bedded sandstones. It underlies areas of low relief
	—Fault—		
Mississippian	Madison limestone	715	Gray to gray-blue thin-bedded to thick-bedded fossiliferous pure to sandy limestone, which weathers to pitted surface
Devonian	Jefferson limestone	498	Brown to black slabby to blocky sandy magnesian limestone with white to gray to buff sandstone, which changes along strike to quartzite. Two specimens of <i>Atrypa reticularis</i> found
Ordovician	Bighorn limestone	890	Light gray brittle seamed dolomitic limestone and sandy limestone which weathers to pitted surface
Cambrian	~Unconformity~ Gallatin limestone	180	Blue dense fossiliferous limestone with thin layers of edgewise conglomerate
	Gros Ventre shale	450-800	Dark green fissile shales with thin gray fossiliferous limestones
	Death Canyon limestone	180+	Dark gray massive seamed limestone with thin shale lenses

thin-bedded calcite-veined limestone with a few dark shale layers. No fossils were found. The top of the unit was drawn at the bottom of the overlying green shales. The thickness of the formation is variable, as parts are faulted out; the maximum thickness is 180 feet.

Gros Ventre shale.—The Gros Ventre is green fine-grained fissile soapy micaceous glauconitic shale with brown mottling on weathered surfaces. Within the shale are thin limestones 10–20 feet thick. They are mottled gray and tan and are finely crystalline thin-bedded fossiliferous and glauconitic. Numerous trilobite cephalons and pygidia were found along with worm borings. The fossils were found only in the limestones. The thickness ranges from 450 to 800 feet. The area in which the thickness is apparently 800 feet is one of abnormally high dips, up to 80°. The formation may be abnormally thick or partly repeated by folding or faulting, although there is no visible evidence of this. In the exposures in which the dip is 38°–40° the thickness is 450 feet.

Gallatin limestone.—The Gallatin conformably overlies the Gros Ventre. It is dark blue thin-bedded dense fossiliferous limestone with some calcite veining. At the base there is a 5–8-foot bed of edgewise pebble conglomerate, which has pebbles covered with glauconite. Shells of brachiopods and trilobites are all oriented in a plane parallel with bedding; it is difficult to obtain good specimens, however, because the limestone will not break readily in a plane parallel with bedding. Sandy shale layers a fraction of an inch thick occur within the limestone and create the thin-bedded appearance characteristic of the limestone. Abrupt nearly vertical slopes are characteristic of its outcrops. The formation is 180 feet thick.

ORDOVICIAN ROCKS

Bighorn limestone.—The Bighorn overlies the Cambrian succession with an angular discordance of 3°–6°. It is light gray dense massive fractured fossiliferous dolomitic limestone and sandy limestone with extensive calcite veining. Its exposures weather to form a rough pitted surface on westward-dipping slopes. Among the fossils found are *Endoceras* sp., corals, brachiopods, and crinoid stems. The structure of smaller fossils has been largely destroyed by replacement. The Bighorn is more easily eroded than the adjacent limestones and commonly forms a strike valley. The Bighorn is 890 feet thick.

DEVONIAN ROCKS

Jefferson formation.—The Jefferson disconformably overlies the Bighorn without noticeable angular discordance. It is a dark brown

medium-grained slabby to blocky sandy magnesian limestone with calcite-filled cavities. Lying 216 feet above the base is a 16-25-foot gray to buff thin-bedded to blocky sugary friable sandstone, which changes along strike to quartzite. A few specimens of *Atrypa reticularis* were found in the magnesian limestone. The Jefferson is 498 feet thick. The formation is divisible into an upper 257-foot magnesian limestone, a 16-25-foot sandstone member and a lower 216-foot magnesian limestone.

MISSISSIPPIAN ROCKS

Madison formation.—The Madison overlies the Jefferson with apparent angular conformity. It is a deep blue dense thin-bedded to thick-bedded fractured fossiliferous calcite-seamed limestone that weathers to a light gray color and has a pitted surface on westward dipping slopes. The surfaces formed by weathering on eastward-facing slopes or cliffs are covered by a yellow-orange coating and chips are easily broken out. At the base is a 75-foot gray thin-bedded to platy sandy limestone that weathers tan and contains *Spirifer centronatus* and thin layers of gray ribbon limestone. Fossils found are *Spirifer centronatus*, *Leptaena* sp., *Schuchertella* sp., *Straparollus* sp., and replaced corals. The maximum exposed thickness of the formation is 715 feet.

CRETACEOUS ROCKS

Hilliard formation.—The Hilliard is overlain by Paleozoic rocks with fault contact and is also overlain unconformably by Tertiary sediments. The Hilliard is a sequence of light gray soft shales and thin gray sandstones. The shale is gray fine-grained thinly laminated shale that weathers to clay. The sandstones are gray medium-grained thin-bedded friable soft salt and pepper sandstones. Weathering of the formation forms basin-like depressions filled with clay. Fossils found are fragments of *Inoceramus* sp., and *Scaphites* sp. The exposed thickness is 4,200 feet.

Adaville formation.—The Adaville conformably overlies the Hilliard and is in fault contact with the overlying Paleozoic rocks. Only the basal part of the formation is exposed. It consists of white and buff medium-grained blocky to massive soft friable porous cross-bedded sandstones. There are interbedded light gray soft shales, lignitic shale, and coal. No fossils were found. The maximum thickness of Adaville exposed is 1,000 feet. The upper part of the formation is covered by the over-riding block of Paleozoic rocks.

TERTIARY ROCKS

Almy formation.—The Almy unconformably overlies the Paleozoic

and Mesozoic sediments. It consists, for the most part, of conglomerates containing boulders up to 8 inches in diameter. Some of the quartzite pebbles are angular; the greater part are well rounded and uniform. The conglomerate on the west side of La Barge Ridge is composed of boulders. The conglomerates are gray or red, and are interstratified with red clays and shales, and thin sandstones. Light colored sandy clay-shales with beds appearing to have an ash content were mapped in the Almy. These light-colored beds may be the equivalent of the Fowkes formation of southwestern Wyoming. Jurassic derived fossils were found. There are 600 feet of these sediments present in the area.

Knight formation.—The Knight rests on the Almy in apparent angular accordance. There is probably an erosion surface between them. The Knight consists of red soft clay-shales, variegated green and purple clay-shales, and intercalated red and yellow medium-grained massive sandstones. Light gray soft clays occur at various places within the red clay series. The surface cap rock found throughout the most of the basin to the east of La Barge Ridge is a brown slightly conglomeratic sandstone. The conglomeratic sandstone is in the lower part of the formation. Several fresh-water limestones up to a foot thick are exposed in Sec. 21, T. 26 N., R. 113 W. The fossils found were derived and were probably reworked by water. The maximum thickness of the Knight is 300 feet.

Green River formation.—The Green River conformably overlies the Knight. It consists of light gray medium-grained massive friable argillaceous sandstone, black soft fossiliferous paper shales, light tan slabby friable soft sandstone which has carbonaceous films along bedding planes. The whole of the formation is easily eroded and it forms mesas, pinnacles, and badlands. Many imprints of plants were found in the paper shales. The maximum thickness of the Green River in the area is 700 feet.

QUATERNARY ROCKS

Quaternary alluvium.—The only extensive area of alluvium is the floodplain of La Barge Creek. It consists of coarse sands and gravels covered by a sandy loam suitable for raising hay. The thickness of the alluvium ranges from 0 to 75 (?) feet.

POST-MADISON AND PRE-HILLIARD SUCCESSION

The stratigraphic succession from Madison to Hilliard is not represented in the area mapped by the writer, but is well known in an area beginning 10 miles west. The missing succession is either faulted out, or covered by Tertiary sediments. The thickness is approximately

20,000 feet, a figure obtained from Mansfield,⁴ Schultz,⁵ and the writer's knowledge of the succession.

STRUCTURE

PRE-TERTIARY

The Paleozoic rocks on the west side of La Barge Ridge dip 33° – 78° W.; the dips generally steepen southward and are steepest on the flanks of the cut formed by La Barge Creek, in Sec. 19, T. 26 N., R. 113 W.

Three isolated masses of Jefferson limestone in Secs. 6 and 7, T. 26 N., R. 113 W., rest on middle Bighorn, which dips 34° W. The northern remnant is composed of Jefferson chips. The northern part of the middle remnant consists of chips and the southern part of blocks up to 12 feet across in which stratification dips 10° W. The base of the southern remnant is a block of Jefferson dipping 12° W.; it is covered by limestone chips. The remnants could have been formed as follows.

1. The Jefferson masses were brought into their present position by a thrust fault, which was nearly parallel with the bedding in the Jefferson and became a horizontal thrust fault at the upper limits of the formation. Thus the limestones of the present remnants moved up the gently dipping thrust, east on the horizontal thrust, and came to rest on the middle Bighorn. The principal objection to this hypothesis is that there is no evidence of the thrust to the west of the remnants.

2. The masses are land-slip or talus breccia formed at a time when the main outcrop of the Jefferson to the west stood out as a ridge much higher than the present one, the crest of which is only 50 feet above the intervening valley. This hypothesis would account for the breccia in the isolated masses, but would not explain the consistency of strike and dip of stratification in the larger blocks.

3. The remnants are parts of fallen cavern roofs. At one time the water table was at a higher elevation than at present. Caverns were formed in the Bighorn limestone, which is more soluble than the underlying and overlying limestone, as the Jefferson and Gallatin now stand out as ridges above the strike valley on the Bighorn. As the caverns grew in size, their roofs began to fall in; this resulted in chips and blocks of Jefferson collecting on the cavern floors. This hypothesis accounts for the breccias, the distance of the isolated masses from the formation outcrop, the consistency of strike and dip of stratification

⁴ G. R. Mansfield, "Geology, Geography, and Mineral Resources of Part of South-eastern Idaho," *U. S. Geol. Survey Prof. Paper 152* (1927), pp. 48–118.

⁵ A. R. Schultz, *op. cit.*, pp. 27–76.

in the larger blocks, and the fact that the westward dips in the Jefferson blocks are less than those of the underlying middle Bighorn.

The Adaville and Hilliard on the east side of La Barge Ridge dip 34° – 37° W. Cross-laminated Adaville sandstones in Secs. 5 and 7, T. 26 N., R. 113 W., show that the formation is not overturned. The upper part of the Adaville is covered by the block above the fault. The Darby fault on the east side of La Barge Ridge is covered by younger rocks in the southern part of the area and extends to the

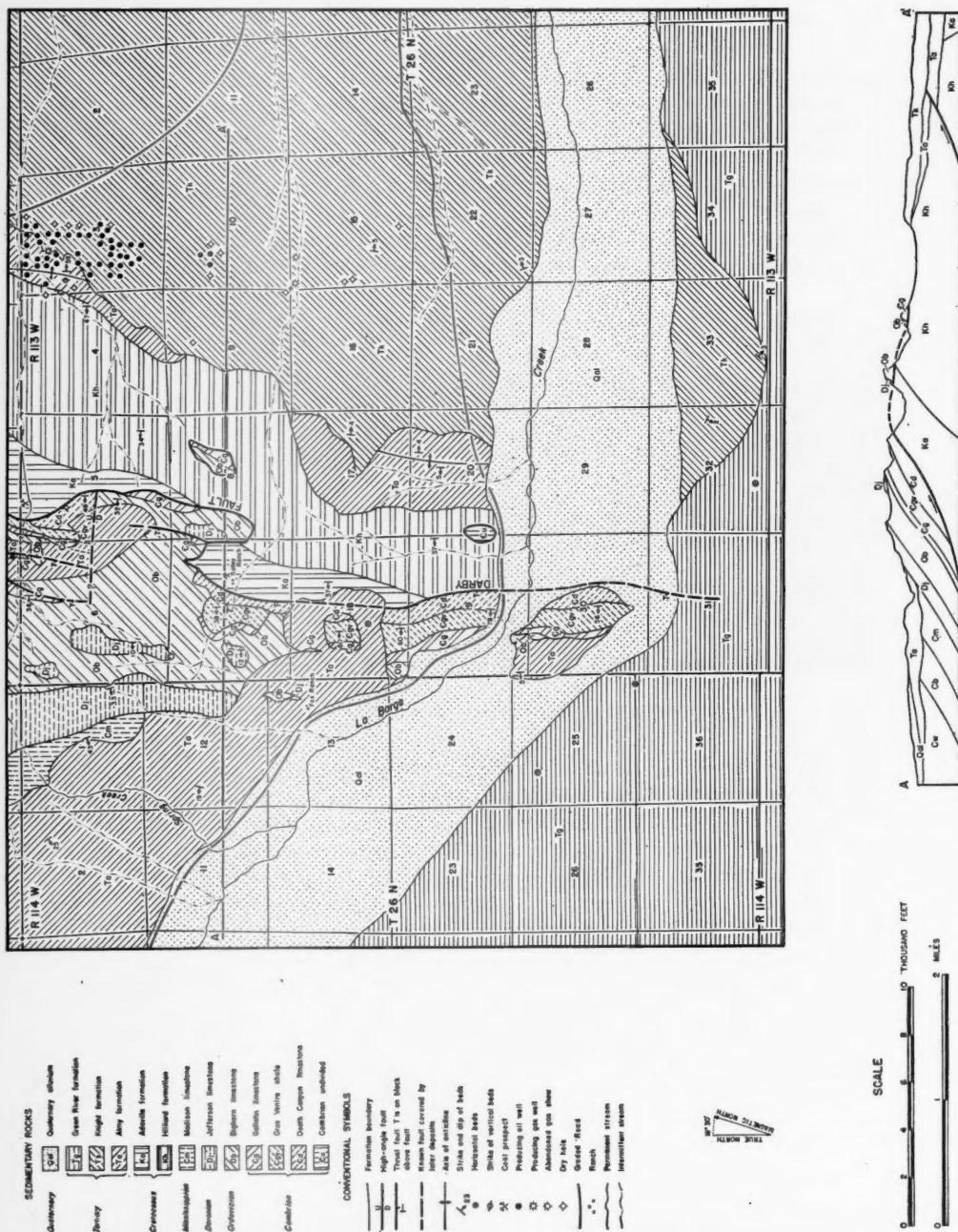


FIG. 2.—Semi-fenster at Salley's Ranch, looking north.

north for approximately 120 miles.⁶ The fault has a general westward dip, but nowhere in the writer's area is it possible to obtain a dip on the thrust plane. At places where the Death Canyon lies on Hilliard, as in Sec. 19, T. 26 N., R. 113 W., 30,000 feet of beds found a few miles west are faulted out. The net slip is therefore at least $5\frac{1}{2}$ miles and probably several times as much dependent on the respective strikes and dips of beds and thrust west of the surface trace of the thrust.

At Salley's Ranch in Sec. 7, T. 26 N., R. 113 W., a semi-fenster (Fig. 2) is shown by the curved trace of the fault (Fig. 3). The fault plane is at approximately the same elevation on both sides of the semi-fenster, which indicates that the thrust is here nearly horizontal. In Sec. 8, T. 26 N., R. 113 W., an isolated mass of Gallatin and Bighorn rests on the Hilliard. Another mass in Sections 19 and 20 of the same township is composed of Gallatin, Gros Ventre, and Death Canyon

⁶ G. R. Mansfield, *op. cit.*, p. 381.



limestones and shales and shows the same relation to the Hilliard. Both are 150-300 feet below the surface trace of the fault at the west. It is possible that the Paleozoic remnants attained their present position by movement down eastward-dipping landslide faults long after the movement on the thrust. It is the writer's belief, however, that they are klippen which were at one time part of the block above the thrust fault, which here dipped eastward at a low angle.

The Gallatin in the NE. $\frac{1}{4}$ of Sec. 7, T. 26 N., R. 113 W., dips 55° NW. It is in normal stratigraphic position under the Bighorn at the west, and in fault contact with the Jefferson on the east. The Gallatin was probably brought into its present position by a high-angle thrust or reverse fault branching upward from the main thrust. The minor fault must necessarily dip west at an angle greater than the dip of the beds in order to produce repetition. In the NW. $\frac{1}{4}$ of Sec. 8, lower Bighorn is in contact with lower Jefferson and in the SW. $\frac{1}{4}$ of Sec. 5, part of the Bighorn is repeated. The fault therefore decreases in displacement northward and probably dies out beneath the Almy.

Several faults occur in the NE. $\frac{1}{4}$ of Sec. 6, and the NW. $\frac{1}{4}$ of Sec. 5, T. 26 N., R. 113 W. West of the center of Section 5, the Death Canyon on the north side of a west-striking fault is in contact with Bighorn on the south side. The north block is relatively upthrown, and beds 600-650 feet thick are faulted out. In the E. $\frac{1}{2}$ of Sec. 6, and the W. $\frac{1}{2}$ of Sec. 5, the bottom of the Bighorn is offset left approximately 3,000 feet, a figure obtained by projecting the bottom of the Bighorn along strike to the fault. North of the fault the Gallatin and Bighorn are repeated by two faults striking north. The dips of beds near these are toward the west, steeper than those of the beds farther west in unfaulted territory, and steeper than those of beds south of the west-striking fault. The western exposure of Gallatin lies in normal stratigraphic position under the Bighorn on the west, and is in fault contact with the Bighorn on the east. The second exposure of Gallatin on the east is in sedimentary contact with the Almy on the west, and in fault contact with Bighorn, which is covered in part by Almy, on the east. The third exposure of Gallatin is in normal stratigraphic position with respect to the overlying and underlying sediments.

The writer believes that the west-striking fault is a tear that probably terminates downward on the main low-angle thrust, and that the two faults north of the tear are high-angle westward-dipping thrusts or reverse faults branching upward from the main thrust and terminating laterally at the south against the tear. In order to produce repetition, they must have dips greater than that of the beds. The two blocks north of the tear moved relatively eastward and upward along

the main low-angle thrust, and were at the same time rotated on horizontal axes striking north so that, when viewed looking northward along the axes, the rotation would be counter-clockwise. This explanation accounts for the Death Canyon in contact with the Bighorn at the east end of the tear, the offset of beds at the left, and the greater dips of beds in the block north of the tear.

The faults described so far are younger than Adaville and older than Almy, as the Almy lies across the main thrust in Sec. 18, T. 26 N., R. 113 W., and shows no evidence of subsequent disturbance.

TERTIARY

The Tertiary sediments surround La Barge Ridge, and in some places the crest of the ridge is lower than the erosion surface truncating them.

The Almy was probably deposited over the whole of the area now occupied by the ridge and filled in depressions in the Paleozoic succession. In Sec. 18, T. 26 N., R. 113 W., the Almy now extends across the crest of the ridge; at this place the beds are horizontal (Fig. 4).

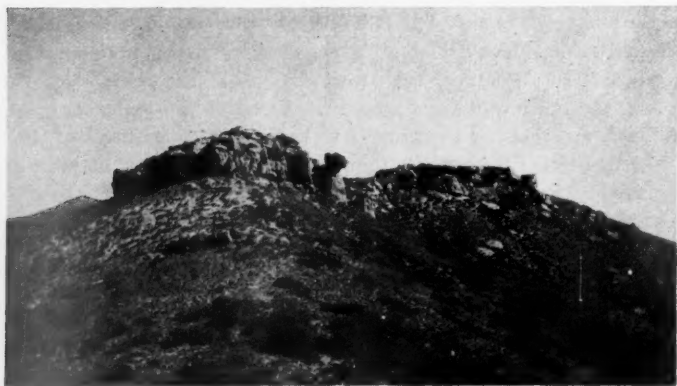


FIG. 4.—Horizontal Almy sediments on crest of La Barge Ridge, Sec. 18, T. 26 N., R. 113 W.

Dips up to 25° on the west side indicate folding or arching in post-Almy time. Minor folds and thrusts formed by a second period of movement occur in the eastern part beneath the Knight. A secondary fault, now known as the La Barge fault, parallels the Darby fault; the secondary fault is recognized in the area studied by the writer from subsurface data, and from surface evidence in the area on the north.

No folding or faulting is shown in the overlying Knight, thus dating the secondary folding and faulting as younger than Almy and older than Knight.

The Knight does not cross the crest of the ridge at present and does not lie directly on Paleozoic rocks. In the area studied by the writer it is confined to the east side of the ridge, and here the eastward dips of 4° – 5° are low enough to be explained as depositional dips. It is therefore probable that the ridge was in existence during Knight time,

The erosion surface truncating the Green River formation in Sec. 31, T. 26 N., R. 113 W., is higher than the surface of the Paleozoic inlier in Section 30, and of about the same elevation as the surface of the Paleozoic rocks in the northern part of Section 19. In Section 31 the Green River is arched into a very gentle anticline plunging southward. The dips are so low that they can not be measured with a Brunton; the anticline is, however, readily visible from the crest of the ridge in Sections 18 and 19. The anticline may have been formed by very gentle horizontal compression in post-Green River time. It is more probable, however, that La Barge Ridge existed in Green River time, the sediments lapped onto its flanks, and the gentle anticline is a fold resulting from differential subsidence during compaction of a succession of sediments thickening away from the buried ridge.

LA BARGE OIL FIELD

The southern end of the La Barge field is in the northeastern part of the area. The surface formation here is the Knight, which covers all underlying structure. H. F. Davies⁷ says,

Parallel with the Darby thrust is a smaller fault, now called the La Barge fault, which has thrust Adaville and Hilliard beds of Upper Cretaceous age over the Almy formation of the Eocene. A small anticline was formed in the Eocene beds in front of the La Barge fault and oil that originated in the underlying unconformable Upper Cretaceous beds has accumulated in the basal sandstones of the Eocene.

This conclusion is substantiated by information received by the writer from operators in the southern part of the field. They report drilling through the Knight and Almy, into Hilliard, and into Almy again, in which production was obtained. The repetition of the Almy can result only from a thrust fault whose west block is upthrown.

HISTORY

The sequence of events in the history of the area is as follows.

⁷ H. F. Davies, "Structural History and Its Relation to the Accumulation of Oil and Gas in the Rocky Mountain District," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), pp. 692–93.

1. Deposition of sediments from Cambrian to Cretaceous in age
2. Strong folding and thrust faulting. Cambrian sediments were brought into contact with Cretaceous sediments
3. Erosion of rocks to depths as great as 30,000 feet
4. Deposition of Almy sediments over entire area
5. Secondary folding and thrust faulting. Almy sediments were folded and Hilliard was thrust onto Almy in eastern part of area. In western part, Almy was tilted possibly as much as 25°
6. Erosion of Almy. Almy sediments were eroded from part of area, but survived on both sides of ridge and in at least one place on crest
7. Deposition of Knight, probably in overlapping relation on east side of ridge. If it was deposited on west side, it has not survived
8. Deposition of Green River formation
9. Gentle arching of Green River, possibly by differential compaction
10. Erosion to present land surface

The main thrust near the crest of the ridge is younger than Adaville and older than Almy; the secondary thrust encountered in wells is younger than Almy and older than Knight.

ECONOMIC RESOURCES

There is no evidence of igneous activity in this area; therefore, it is improbable that there are any metallic mineral deposits. Crystalline gypsum is found on several of the Almy and Hilliard slopes in the east-central part of the area, but not in large enough quantities to be of economic importance.

Coal seams in the Adaville have been exploited to a limited extent, but at present are worked only for ranch use. The larger users truck in coal of better quality from the Kemmerer coal field. A prospect or surface pit is located in Sec. 5, T. 26 N., R. 113 W., and a mine, which is worked during the winter to supply local ranches, is adjacent to Salley's Ranch in Sec. 7, T. 26 N., R. 113 W. The Twitchell mine about 2 miles north of the prospect in Section 5 has been worked in the past.

The discovery of oil in the La Barge field in 1907 caused considerable excitement and development.⁸ Oil and gas are now produced in Secs. 3 and 10, T. 26 N., R. 113 W. The fact that operators drill through the Almy, then Hilliard, and into Almy, in which they obtain production gives evidence for the fault trap shown in cross section AA' (Fig. 3). The oil escapes from the oil-generating Cretaceous rocks beneath the secondary fault, and migrates upward into the basal Almy sands of the east block. Marginal drilling may prove a greater area of production in the Tertiary sediments. Deep tests may prove an anticline in the underlying Cretaceous beds, of which Schultz⁹ says,

⁸ A. R. Schultz, *op. cit.*, p. 116.

⁹ *Ibid.*, p. 79.

The crest of the La Barge Anticline is exposed along the east side of La Barge Ridge in only two localities, at both of which numerous minor folds are visible. Throughout the remainder of the region the anticline is covered by Tertiary deposits, which commonly dip regularly eastward across it and give no hint of its position.

The gas is used for repressuring, power production, and local domestic fuel. The oil is piped to Opal on the Union Pacific Railroad about 45 miles southeast.

UNDERGROUND WATER

Because the water supply of the ranchers has been obtained from La Barge Creek and springs in the area, no wells except those in the La Barge field have been drilled.

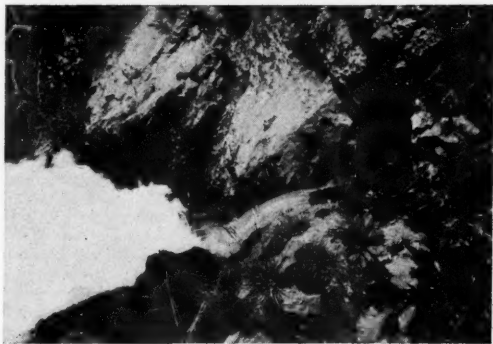


FIG. 5.—Spring on west side of La Barge Ridge, Sec. 1, T. 26 N., R. 114 W.

A spring in the NW. $\frac{1}{4}$, NW. $\frac{1}{4}$ of Sec. 1, T. 26 N., R. 114 W., discharges water under pressure from open fractures in the Madison limestone in a circular area approximately 7 feet in diameter. The water forms a stream, Spring Creek, 8 feet wide of average depth of 6 inches flowing at least 2 miles an hour. The flow, based on these figures, is at least 10 second feet. In the area on the north, the outcrop of the Madison provides a large catchment area. In Section 1 the Madison is deeply dissected; this furnishes an outlet for the water in the Madison at a low elevation. Solution caverns in the Madison act as reservoirs.

A spring in the NW. $\frac{1}{4}$, SE. $\frac{1}{4}$ of Sec. 7, T. 26 N., R. 113 W., comes out of a sandy lens in the Gros Ventre. The water flows to the surface,

and forms a stream of approximately 2 second feet. The Bighorn is probably the reservoir rock from which most of the water coming to the surface is derived. Water, accumulated in the Bighorn, seeps downward to the fault plane, and flows up the fault plane to a place of easy escape.

Water for irrigation purposes could be obtained by drilling wells in the Quaternary alluvium; however, this has not yet been done, as water from creeks and springs is sufficient to supply present demands for irrigation and domestic purposes.

CORRELATION OF CROSS' LA PLATA SANDSTONE, SOUTHWESTERN COLORADO¹

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ABSTRACT

The Upper Jurassic La Plata sandstone, described by Cross as essentially two thick sandstones with a thin limestone between, is shown to consist typically of the following units in ascending order. Unit 1 is the Entrada sandstone, a massive, partly cross-bedded, yellowish to red sandstone. Unit 2 is discontinuous bituminous, thin-bedded limestone, in places associated with gypsum, attaining a thickness of 15 feet, and named the Pony Express limestone member of the Morrison formation. Unit 3 is sandstone or sandy beds about 20 feet thick here named the Bilk Creek sandstone member of the Morrison. At the top of this member there is a sandstone about 1½-2 feet thick, with coarse rounded grains and autochthonous red chert, called carnelian sandstone. Unit 4 consists of 50-100 feet of red, sandy, cherty marls, named the Wanakah marl member of the Morrison, a restriction of the name to only that part of the section to which it was originally applied. The Wanakah marl contains crystals or concretions of barite and a zone of chert concretions coated with a green mineral. This zone is a valuable diagnostic bed in correlation. Unit 5 is massive, cross-bedded, whitish sandstone attaining a thickness of 500 feet, here named Junction Creek sandstone member of the Morrison. In places beds of Wanakah type overlie the Junction Creek sandstone and make it more difficult to draw, the boundary against the overlying beds.

Unit 1, the Entrada, is Cross' lower La Plata sandstone. Unit 5 is thickest in the La Plata Mountains and is the upper La Plata sandstone of that region. In the Telluride region, where this bed is poorly developed or absent, the Bilk Creek sandstone (unit 3) has been called upper La Plata sandstone. In other areas, where both the Pony Express limestone (unit 2) and the Junction Creek sandstone (unit 5) are absent or poorly developed, the Bilk Creek sandstone has been regarded as part of the Entrada, and beds probably younger than the Junction Creek have been called upper La Plata sandstone. We believe that units 2 and 3 are equivalent to the Curtis of east-central Utah, and unit 4 to the Summerville, and that unit 5, the Junction Creek sandstone, hitherto recognized only as the upper La Plata sandstone of the La Plata Mountains, bears more resemblance to the Wingate, Navajo, and Entrada sandstones of the Utah section than to the overlying Morrison sandstones. Pending further studies in this area they are, however, all classed here as members of the Morrison formation.

In southeastern Utah the Bluff sandstone member of the Morrison may be equivalent to the Junction Creek. We incline to Gregory's interpretation that the Todilto limestone in Todilto Park is overlain by the Navajo sandstone and is, therefore, not equivalent to the Pony Express limestone; but on Beclabito (Biltabito) Dome in the northwest corner of New Mexico, the limestone called Todilto lies on the Entrada, is overlain by beds resembling the Wanakah, and we, therefore, consider it equivalent to the Pony Express. Possible equivalents of the Junction Creek sandstone in New Mexico are pointed out. A tentative correlation of a section along the Cimarron River, in the northeast corner of New Mexico, with the southwest Colorado section, is proposed. The presence, in places, of a series of yellowish sandy shales and regularly bedded, sideritic sandstones, that may be intermediate in position between the horizon of the top of the Junction Creek and the overlying Morrison sandstones, is pointed out.

INTRODUCTION

The correlation of the beds previously assigned to the La Plata sandstone has always been uncertain. As several papers dealing with the ore deposits of southwestern Colorado are in preparation by the

¹ Published with the permission of the director, Geological Survey, United States Department of the Interior. Manuscript received, April 14, 1941.

² Geological Survey, United States Department of the Interior.

staff of the Geological Survey, United States Department of the Interior, it was desirable to clarify the correlation, between the mining districts in Colorado, of the units that have been called La Plata sandstone and to reconsider certain features of recent correlations between Colorado and adjacent states.³ In the field season of 1938 the problem was, therefore, attacked by Goldman, and in 1939 by Spencer and Goldman working together. The work was part of a geologic program undertaken by the Geological Survey in coöperation with the State of Colorado and the Colorado Metal Mining Fund.

ANALYSIS OF SOUTHWESTERN COLORADO SECTION

According to the "Lexicon of Geologic Names of the United States"⁴ the name La Plata sandstone was given by Cross and first published in 1898.⁵ It was derived from the La Plata Mountains in southwestern Colorado, where the beds in question are particularly well developed. The name came to be applied to different units and is not now used in publications of the Geological Survey.

Descriptions and graphic sections of the La Plata sandstone are given in the following folios of the Geological Survey: "Telluride," No. 57 (1899); "La Plata," No. 60 (1899); "Rico," No. 130 (1905); "Ouray," No. 153 (1907); "Engineer Mountain," No. 171 (1910). (See Fig. 1.)

The graphic sections in these folios represent the formation as consisting of a thin limestone between two sandstones, the sandstones generally much thicker than the limestone. In the La Plata, Rico, and Engineer Mountain folios, the accompanying text states in part, "*Principally*⁶ two massive . . . sandstone beds with a narrow band of . . . limestone . . . between."

Actually we find that, beginning at the base, the following five members may readily be differentiated in the section covered by the name La Plata sandstone.

Unit 1 is thick, massive, in part cross-bedded, yellow to red sandstone.

Unit 2 is dark gray to black bituminous limestone, discontinuous and variable in character. Where best developed in the area examined, it attains a thickness of about 15 feet, and is in part shaly, in part

³ Cf. A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Correlation of the Jurassic Formations of Parts of Utah, Arizona, New Mexico, and Colorado," *U. S. Geol. Survey Prof. Paper* 183 (1936).

⁴ M. G. Wilmarth, "Lexicon of Geologic Names of the United States," *U. S. Geol. Survey Bull.* 896, Pt. 1 (1938), p. 1149.

⁵ C. W. Purington, *U. S. Geol. Survey 18th Ann. Rept.*, Pt. 3 (1898), p. 759.

⁶ Italics ours.

more solidly bedded. Near the northern limit of its extension, along the Uncompahgre River, between Ouray and Ridgway, in the Ouray Quadrangle, the upper part of the limestone is largely replaced by gypsum or by a limestone breccia derived from solution of the gypsum in a gypsum-limestone complex.⁷ On the Piedra River, near the south-

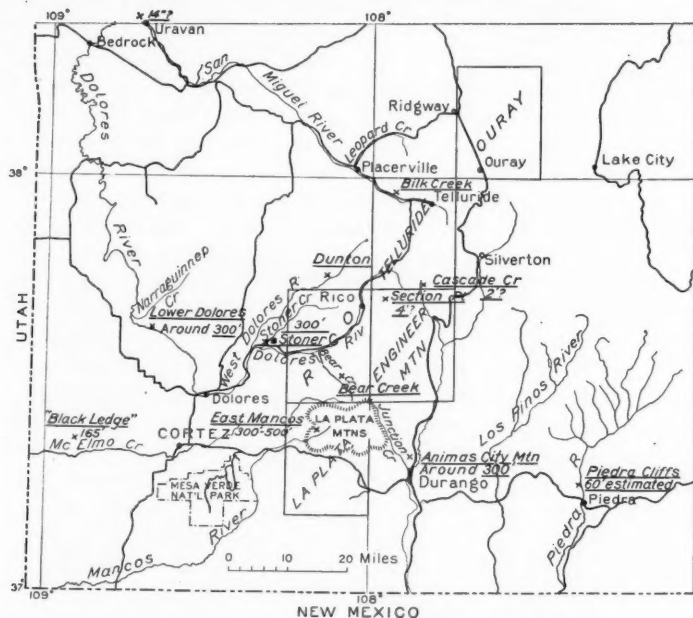


FIG. 1.—Map of southwest corner of Colorado showing localities studied for this report. Crosses mark points at which sections were measured. They are accompanied by name used for locality and—where Junction Creek sandstone member of Morrison formation has been recognized—by number giving its approximate thickness there. Areas covered by Geological Survey folios, in which La Plata sandstone is described, are outlined. Heavy winding lines represent roads.

eastern limit of its exposure in Colorado, shales in the lower part contain fossil fish of fresh water type,⁸ but few fossils of any kind have been found in the limestone anywhere.

Unit 3 is sandstone or a succession of sandy beds, generally about 20 feet thick, rather soft, with prevailing horizontal, and locally

⁷ W. S. Burbank, "Revision of Geologic Structure and Stratigraphy in the Ouray District of Colorado, etc.," *Proc. Colorado Sci. Soc.*, Vol. 12, No. 6 (1930), p. 175.

⁸ Whitman Cross and Esper S. Larsen, "Contributions to the Stratigraphy of Southwestern Colorado," *U. S. Geol. Survey Prof. Paper* 90-E (1914), p. 47.

ANIMAS CITY MTN

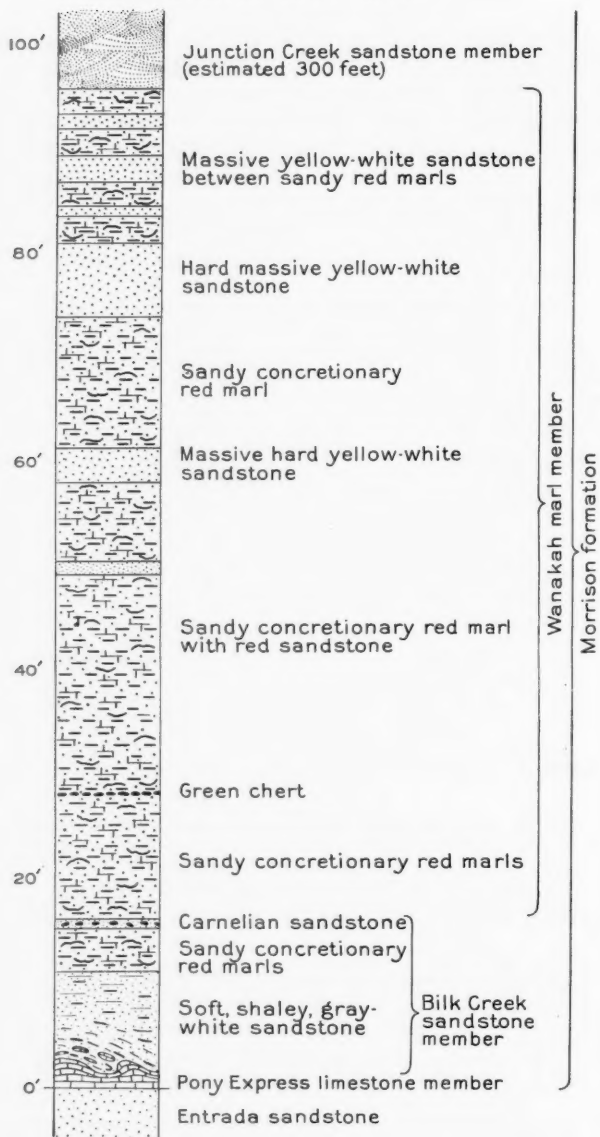


FIG. 2.—Section at Animas City Mountain, Colorado, showing upper part of Entrada sandstone, lower part of Junction Creek sandstone member of Morrison formation, and beds between them.

nodular bedding, and of finer grain than the sandstone of unit 1. At the top of this member there is hard, thin, ledge-forming, calcareous sandstone, probably sideritic, with many coarse, rounded grains, pale yellowish white on a fresh surface, weathering brown, with flat, vertical joint faces and roundish upper edge. It generally contains autochthonous red chert, scattered through it to some extent but more characteristically on its upper surface. Cross and his associates gave the field name "carnelian sandstone" to this bed. Even in the absence of red chert, however, it can usually be recognized by the other features mentioned. In most places it is about $1\frac{1}{2}$ -2 feet thick.

Unit 4 is a succession, 50-100 feet thick, of hard, calcareous, concretionary, sandy, red, argillaceous beds with some thin sandstones. Five to 15 feet above the base of this member there is generally a zone a few inches thick containing chert concretions. This is a rather complicated zone, discontinuous, varying in its local details within short distances and in its larger features between more widely separated localities, but characterized by the occurrence of thin layers of material of a rich, dark green color on red chert concretions. In the section measured near Bilk Creek (Fig. 3) the red chert layer is about 2 inches thick and is underlain by about $\frac{1}{2}$ inch of laminar, calcareous, concretionary material. In other places the chert is black instead of red, and there are many other minor variations. But the significant and diagnostic feature is the distinctive green mineral, and its common association with a thin chert layer. This green mineral may be of glauconitic or chloritic composition. A specimen tested in the laboratory of the Geological Survey was rich in potassium. It is unlike typical marine glauconite in that it occurs as coatings on concretions instead of as round grains, but C. S. Ross of the Geological Survey says it may well be a form of this mineral, as glauconite varies greatly in mode of origin and in character. At some localities barite occurs in this member, either as scattered elongate crystals in some of the sandstones or as concretions lying between some of the higher sandstones. In the upper part of the member the barite may occur in a definite sandstone, but we were not able to establish this restriction, and in McElmo Canyon (Fig. 6) it occurs as low in the section as the carnelian sandstone. It is characteristic of this member that where it is more sandy the sandy beds or sandstones increase in proportion upward.

Unit 5 is massive, whitish sandstone, generally with cross-bedding of the eolian type, and with considerable rounding of the grains. In many of its exposures, as in the Dolores valley at and around Stoner and below McPhee, it is divided conspicuously into two parts, a lower more horizontally banded part with diagonal bedding within the hori-

zontal layers, and an upper part with diagonal bedding on a large scale, that is, a single direction of diagonal bedding extending across a horizontal layer as much as 60 feet thick and continuing parallel with itself over long stretches, suggesting big decapitated dunes. This sandstone attains thicknesses as great as 500 feet. This is the white, cliff-forming sandstone of the White Cliffs on the East Mancos River on the west side of the La Plata Mountains.

The most complete exposure of the aforescribed section that we have found is in the north wall of the valley bounding Animas City Mountain on its north side, about a mile north of Durango, Colorado, on the southeast flank of the La Plata Mountains.

From evidence to be presented we correlate the basal sandstone, unit 1 of this sequence, with the Entrada sandstone of Utah.

For the other units, which are for the present classified as members of the Morrison formation, we propose the following names.

From the limestone (unit 2)—Cross' La Plata limestone—we use the name Pony Express limestone, from the name applied to it by miners in the Ouray mining district. According to the "Lexicon of Geologic Names of the United States"⁹ the name was first used in print by Irving.¹⁰

For the 20 feet or so of sandstone or sandy beds (unit 3) resting directly on the limestone and capped by the carnelian sandstone, we propose the name Bilk Creek sandstone, from a section above the highway about 6 miles west of Telluride, along the San Miguel valley, opposite the mouth of Bilk Creek and directly above an old lime kiln¹¹ (Fig. 3). For the thin sandstone at the top of the Bilk Creek sandstone, we use the name "carnelian sandstone."

For the sandy, red, argillaceous beds (unit 4) between the carnelian sandstone and the thick, massive sandstone of the La Plata Mountains we here use the name Wanakah marl. This usage of Wanakah is a restriction of the original usage by Burbank,¹² for he included in it not only this shale unit but also the underlying Pony Express limestone and Bilk Creek sandstone. On account of the high carbonate content of the argillaceous beds of this member, marl seems the appropriate term to apply to them.

For the upper sandstone (unit 5) we propose the name Junction

⁹ M. G. Wilmarth, *op. cit.*, p. 1699.

¹⁰ J. D. Irving, "Ore Deposits of the Ouray District, Colorado," *U. S. Geol. Survey Bull.* 260 (1905), Fig. 1, p. 56.

¹¹ Cf. Whitman Cross, "Telluride," *U. S. Geol. Survey Geol. Atlas Folio* 57 (1899), p. 3.

¹² W. S. Burbank, *op. cit.*, p. 172.

Creek sandstone, from the excellent exposure opposite Animas City Mountain (Fig. 2) between Junction Creek and the Animas River.

In the following text the proposed names, for the present to be treated as names of members of the Morrison formation, are used in many places without the qualifying terms "member of the Morrison formation" unless the context requires it for clarity.

Clarification of the stratigraphy of the beds formerly called the La Plata sandstone involves two distinct problems. One is to determine the relation to each other of beds that have been called La Plata sandstone in different parts of southwestern Colorado; the other is to correlate these beds with beds in the Jurassic sections of southeastern Utah and northern New Mexico.

CORRELATION IN SOUTHWESTERN COLORADO

Using the diagnostic features already described, especially the "green chert" zone, we find that sandstones at three different horizons have been called upper La Plata sandstone in southwestern Colorado.

In the area of the Ouray and Telluride folios, represented by the section opposite the mouth of Bilk Creek in the Telluride folio (Fig. 3) the Bilk Creek sandstone has been called upper La Plata sandstone.

At Section Point, in the northwest sector of the Engineer Mountain Quadrangle, the geologic map in the folio indicates that beds forming the summit of the peak, which we regard as younger than the Junction Creek sandstone, have been included in the upper La Plata. The Junction Creek sandstone, if present here, is probably a massive 4-foot sandstone well below the summit.

The Junction Creek sandstone of the La Plata Mountains is the true upper La Plata sandstone.

The confusion that has developed is apparently due to the discontinuity of the Pony Express limestone, to the resemblance, in a general way, of the Bilk Creek sandstone immediately above the limestone to the Entrada sandstone immediately below it, and to the fact that the Junction Creek sandstone, the upper La Plata sandstone of the type area, is well developed over only part of the area in question.

Thus in the section opposite Bilk Creek (Fig. 3) where the limestone is well developed and the Junction Creek sandstone is absent, the Bilk Creek sandstone came to be called upper La Plata sandstone. On the other hand, in the La Plata Mountains, where large areas are covered with brush and forest, where the Pony Express limestone is in places thin and discontinuous and the Junction Creek sandstone is

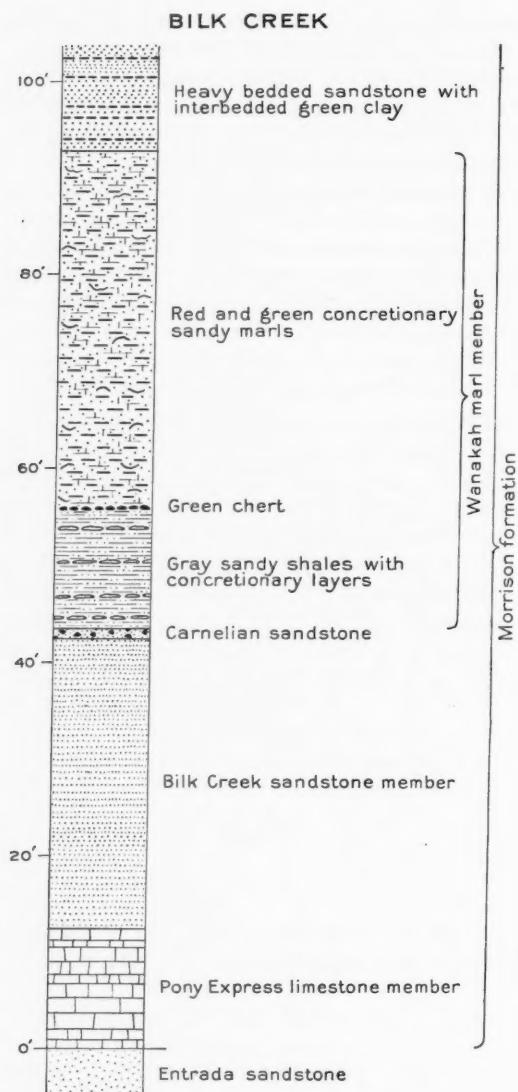


FIG. 3.—Section on San Miguel River opposite mouth of Bilk Creek, near Telluride, Colorado, showing upper part of Entrada sandstone and named members in lower part of Morrison formation.

TABLE I
NOMENCLATURE OF UPPER JURASSIC FORMATIONS IN SOUTHWESTERN COLORADO

<i>San Juan Region, 1936, Prof. Paper 183</i>	<i>La Plata Mountains, 1899, Cross*</i>	<i>La Plata Mountains, This Paper</i>	<i>Bilk Creek, Telluride Quadrangle, This Paper</i>	<i>Ouray District, 1930, Burbank</i>	<i>Ouray (1907) and Telluride (1899) Quadrangles, Cross</i>
Morrison formation	McElmo formation	Morrison formation	Morrison formation	Shale member of Morrison	McElmo formation
				Sandstone member of Morrison	
				Absent	
	Upper sandstone	Junction Creek sandstone member	Absent	Wanakah marl member (restricted)	Shale
		Morrison formation	Bilk Creek sandstone member	Bilk Creek sandstone member (type locality)	Wanakah member of Morrison formation
			Pony Express limestone member	Pony Express limestone member	Sandstone
Entrada sandstone	Lower sandstone	Morrison formation	Morrison formation	Entrada sandstone or Jurassic sandstone	La Plata sandstone
				Lower sandstone	
	Upper sandstone	Morrison formation	Morrison formation	Morrison formation	Lower sandstone
					Upper sandstone

* Two possible alternative interpretations for the sequence below the upper sandstone are here shown and are also discussed in the text.

thick and forms conspicuous cliffs, Cross and his co-workers apparently made one, or both, of two possible interpretations. Either they assumed, where they did not find the limestone, that the calcareous Wanakah marl represented the limestone and that the Bilk Creek sandstone was part of the lower La Plata sandstone, or, where the limestone was well developed, they assumed that the Bilk Creek sandstone was a sandy member in a calcareous sequence between the Entrada and Junction Creek sandstones. In the columnar section in the

CLASSIFICATION OF THIS PAPER ¹		NAMES USED BY CROSS LA PLATA FOLIO, 1899		NAMES USED BY CROSS TELLURIDE FOLIO, 1899
FORMATION	MEMBER			
Morrison formation		McElmo	40 Miles	McElmo
	Junction Creek sandstone	Upper La Plata		
	Wanakah marl	Middle La Plata		
	Bilk Creek sandstone	Middle La Plata		Upper La Plata
	Pony Express limestone	Lower La Plata		La Plata limestone
Entrada sandstone		Lower La Plata		Lower La Plata

FIG. 4.—Diagram showing relation of nomenclature proposed in this paper to earlier nomenclatures. Below upper La Plata sandstone two possible alternative interpretations discussed in text are given.

¹ As explained in text, we believe Pony Express limestone and Bilk Creek sandstone, together, are equivalent to Curtis formation of Utah; Wanakah marl is equivalent to Summerville formation of Utah; and Junction Creek sandstone is pre-Morrison sandstone hitherto differentiated only as upper La Plata sandstone of southwestern Colorado. However, introduction of this new classification would involve redefinition of Morrison in parts of Utah, New Mexico, and Paradox Valley region of western Colorado, where areal mapping by parties of the Geological Survey is now in progress. Consequently, present classification of these beds as Morrison is here retained, pending completion of mapping in certain critical areas.

back of the La Plata folio they say of the La Plata sandstone: "Consists *principally* of two very massive, friable, white sandstones, with a narrow band of dark limestone *or calcareous shale* between them";¹³ and at the top of column 1, p. 4 of this folio, they say: "The limestone is often bluish black. . . . The shales *which replace it* are. . . ."¹⁴

We believe, however, that once the Bilk Creek sandstone is recognized as a distinct unit it is possible, in southwestern Colorado, to differentiate it from the underlying Entrada sandstone, even where the Pony Express limestone is absent, by such characteristic features

¹³ Italics ours.

¹⁴ Italics ours.

as its horizontal, in some places nodular bedding, a parting at its base, its finer grain, its lesser coherence, and a difference in color—either more or less red than the Entrada.

In Figure 1 are given measurements or rough estimates of the thickness of the Junction Creek sandstone at the localities where we identified it.

Table I and Figure 4 illustrate, diagrammatically, our interpretation of the relations of beds that have been called La Plata sandstone in southwestern Colorado.

CORRELATION WITH JURASSIC OF UTAH

The basis of correlation of the La Plata sandstone of Colorado, as thus revised, with the Jurassic of east-central Utah is the section at Uravan, near the western border of Colorado, on the San Miguel River, 4 or 5 miles above its junction with the Dolores River (Fig. 5). Here we differentiated the Bilk Creek sandstone including the carnelian sandstone, and the "green chert" zone in the Wanakah marl. They lie above a massive thick sandstone which, by its red color, its large scale, rather gentle cross-bedding with interbedded horizontal layers, its smooth, rounded weathering face, and its "swallow holes" (small holes weathered into the cliff face, many of them in horizontal rows) is clearly correlative with the Entrada sandstone of adjacent parts of Utah.¹⁵

The Pony Express limestone is absent here and the Bilk Creek sandstone, consisting almost entirely of 20 feet of knobby, concretionary, red sandstones, is separated from the Entrada by only a very thin parting of red clay.

No autochthonous red chert was found in the sandstone here designated carnelian sandstone. But it contains the abundance of coarse round grains characteristic of that sandstone, and, like the carnelian sandstone in many of its occurrences, is concretionary. Note that sandstones with red chert occur higher in the Wanakah here.

The sandstone marked A in Figure 5 may be the equivalent of the Junction Creek sandstone. The 4 feet of sandy red shales overlying it would then be equivalent to beds of Wanakah type that, as will be explained, overlie the Junction Creek sandstone at several localities, and the overlying clays would be post-Junction Creek. The presence of the barite concretions at the base of the clay favors taking this horizon

¹⁵ James Gilluly and J. B. Reeside, Jr., "Sedimentary Rocks of the San Rafael Swell and Some Adjacent Areas in Eastern Utah," *U. S. Geol. Survey Prof. Paper 150-D* (1928), pp. 76-78.

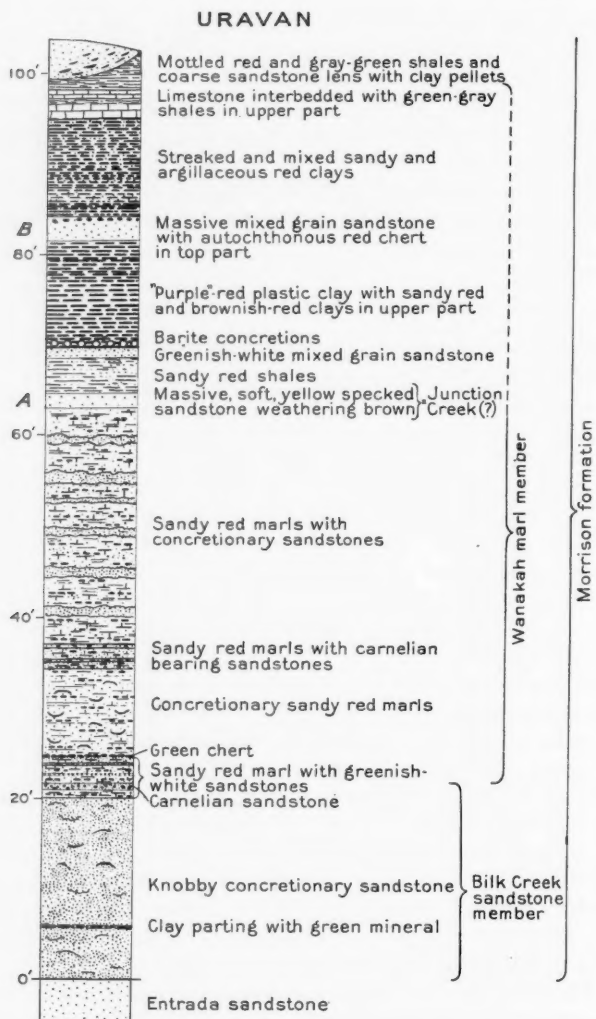


FIG. 5.—Section at UraVan, Colorado, showing upper part of Entrada sandstone and overlying members of Morrison formation.

as the top of the Junction Creek (or Wanakah if the Junction Creek is absent here) for such concretions are, in many places, formed at more pronounced stratigraphic boundaries. Their presence at this horizon

might then be assumed to correspond with the occurrence of a gypsum bed at the contact of Morrison and Summerville in places along the flanks of the San Rafael swell, as sedimentary calcium sulphate and barium sulphate are closely related in origin. However, elsewhere we found concretions of this kind in the upper part of the Wanakah, for instance, on the Dolores River near Stoner.

Moreover, although we believe, as will be explained, that where beds of Wanakah type overlie the Junction Creek sandstone, the contact with the overlying sequence should probably be taken at the base of immediately overlying plastic clays, generally "purple"-red (really an impure dark red¹⁶); nevertheless, there are certain features of these overlying beds here that raise doubts about this assignment. One is that the bed marked *B* in Figure 5 is entirely of the type of the carnelian sandstone, has characteristic disseminated coarse rounded sand grains, and is rather regularly bedded. According to R. P. Fischer of the Geological Survey, this bed appears to be persistent and uniform in character and thickness in the Uravan area. Although we have found no bed of this kind so high in the Wanakah elsewhere, all these features ally it more to this member than to the post-Junction Creek sequence.

Another doubtful feature is the presence of sandy red clays above the "purple"-red plastic clays in an interval better exposed than the interval with "purple"-red clays.

Only the upper part of the interval above bed *B*, represented in Figure 5 by clays, was well exposed, but from what we have seen of the beds above bed *B*, we regard them as more distinctly of the post-Junction Creek type.

The lenticular sandstone at the top of our section we consider definitely of the post-Junction Creek type.

A more detailed study, with fuller exposure, of the beds between bed *A* and the uppermost sandstone of our section at Uravan might lead to more definite conclusions regarding the boundary in question.

As the sandstone underlying the horizon of the Pony Express limestone here is the Entrada sandstone, we have correlated the lower La Plata sandstone throughout with the Entrada. In doing so, however, we intend merely to indicate that no formation known elsewhere to be younger than Entrada underlies the horizon of the Pony Express limestone. It is possible that the sandstone correlated with the Entrada may represent one or more of the older sandstones of

¹⁶ Cf. Robert Ridgway, *Color Standards and Color Nomenclature*. Published by the author, Washington, D. C. (1912). Especially Pls. XXVII and XXXIX, and Pl. XIII, 1st and 3rd.

the Utah section. In east-central Utah the Entrada sandstone is underlain by the Carmel formation, the Navajo sandstone, the Kayenta formation, and the Wingate sandstone. In southwestern Colorado, which is near the eastern border of the area in which these formations were deposited, they are likely to pinch out and merge so that a single sandstone there may occupy the interval that elsewhere includes all the formations from Wingate to Entrada, and may have been deposited at only one time or at different times during that interval. Actually the lower La Plata sandstone has been interpreted¹⁷ as equivalent, in some places, in its lower part to the Wingate sandstone and in its upper part to the Entrada sandstone, and Heaton¹⁸ believes that, in places, the lower part of the sandstone at this horizon may even be of Triassic age. However, in other places the upper part of the redbeds of the Dolores formation underlying the lower La Plata sandstone has been correlated with the Wingate and even with the Navajo sandstone.¹⁹

Any correlation of the beds overlying the Entrada sandstone in southwestern Colorado with those in Utah must, in our opinion, be based on recognition of the fact that the Junction Creek sandstone, by its purity, its eolian type of cross-bedding, the uniform size and relative roundness of its grains, and the great thicknesses it attains, is of the type of the pre-Morrison sandstones of the east-central Utah section, the Wingate, Navajo and Entrada, and not of the type of the sandstones in the Morrison formation. If this fact is accepted a very plausible correlation can be made, of the beds between the Entrada and the Junction Creek sandstones, with the pre-Morrison beds of east-central Utah.

Along much of its outcrop on the northeast flank of the San Rafael swell the top of the Curtis formation is characterized by red chert concretions as much as a foot in diameter; and hard, red, sandy marls of the Summerville, like those of the Wanakah, directly overlie the bed in the top of which these concretions occur. It is, therefore, reasonable to regard the carnelian sandstone as equivalent to the top of the Curtis. In east-central Utah the Curtis is one of the more extensive and characteristic marine members of the Jurassic section. As pre-

¹⁷ A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Correlation of the Jurassic Formations of Parts of Arizona, New Mexico, and Colorado," *U. S. Geol. Survey Prof. Paper 183* (1936). See secs. 46, 21, and 52, Pl. 3, facing p. 20; but compare also Pl. 26C facing p. 59, and p. 23, column 2, paragraph 2, and secs. 69, 55, and 51, pl. 4, facing p. 22.

¹⁸ Ross L. Heaton, "Contribution to Jurassic Stratigraphy of Rocky Mountain Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 8 (August, 1933), pp. 1153-77.

¹⁹ Baker, Dane, and Reeside, *op. cit.*, table 5, opp. p. 39.

viously stated, the Pony Express limestone is not known to contain any marine fossils. But in southwestern Colorado, which is marginal to the area of Jurassic deposition, a period of expansion of marine waters might well be represented, in part, by the limestones and gypsums of the Pony Express limestone. We therefore suggest that the Pony Express limestone and the Bilk Creek sandstone are together equivalent to the Curtis formation of Utah.

The Bilk Creek sandstone appears to be closely related to the Pony Express limestone, for at Animas City Mountain (Fig. 2) and on Leopard Creek²⁰ a few miles north of Placerville near Telluride parts of the Pony Express limestone are kneaded into the Bilk Creek sandstone in a way that suggests that the limestone was still soft when the sandstone was deposited on top of it.

As stated, the Wanakah marl in its color, hardness, and sandy character is very similar to the marls of the Summerville which directly overlie the Curtis in east-central Utah. Although the average size of the sand in the Summerville, along the northeast flank of the San Rafael swell, is finer than that in the Wanakah marl, grains conspicuously rounded characterize the Summerville marls as they do those of the Wanakah. We, therefore, believe that the two formations are equivalent to each other.

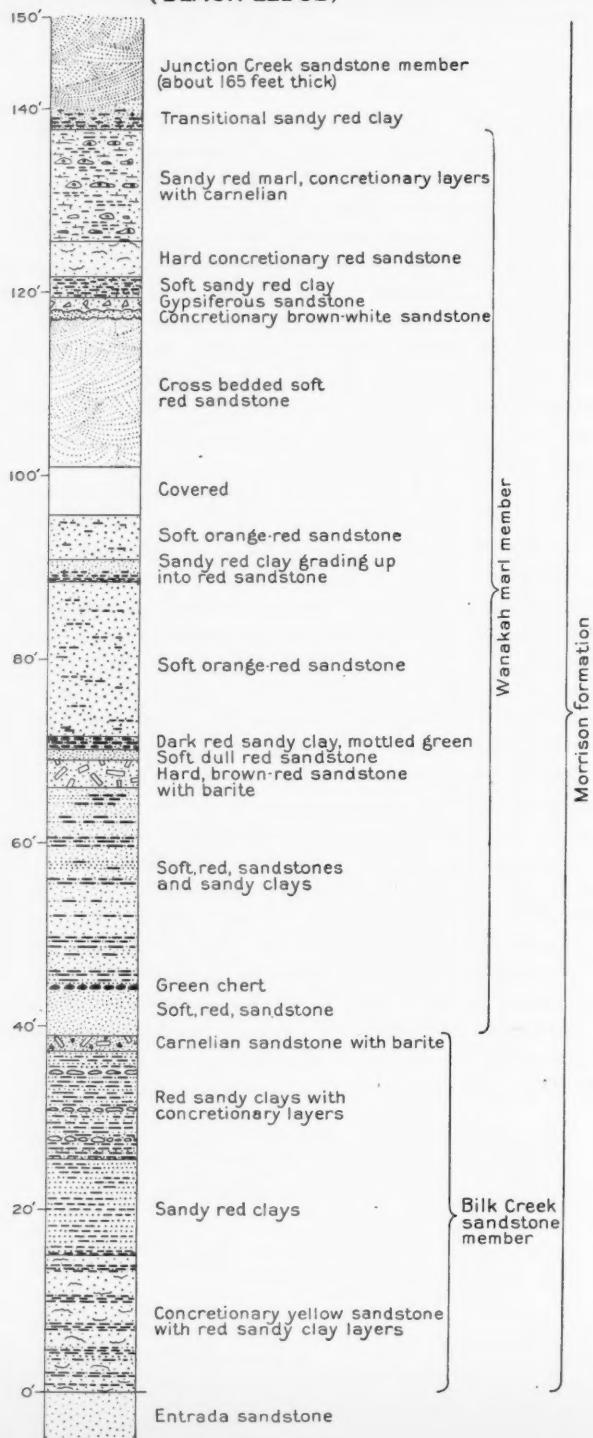
As indicated by Figure 1, the Junction Creek sandstone thins within short distances away from the La Plata Mountains. Nothing that might be equivalent to it has been recognized along the northeast flank of the San Rafael swell. There is good reason, however, for believing that the Bluff sandstone member of the Morrison at Bluff in the southeast corner of Utah, is the equivalent of the Junction Creek sandstone. We found the Junction Creek sandstone well developed in McElmo Canyon only about 35 miles east of Bluff. None of the definite diagnostic members was found in the underlying red beds at Bluff; but, though differing from the Wanakah marl section in several respects, these red beds have several general characters in common with it, and the Bluff sandstone itself, like the Junction Creek sandstone, falls into a lower more horizontally bedded and an upper diagonally bedded part.

POSSIBLE EQUIVALENTS IN NORTHWESTERN NEW MEXICO
OF SEQUENCE FROM ENTRADA SANDSTONE TO
JUNCTION CREEK SANDSTONE

A reconnaissance in northwestern New Mexico leads us to believe that the Junction Creek sandstone may be and that the Pony

²⁰ Communication from W. S. Burbank.

McELMO CANYON ("BLACK LEDGE")



Express limestone is represented in this area, but that there is evidence to indicate that the Todilto limestone at Todilto Park is older than the Pony Express limestone. The nature of our investigation in this area does not justify a detailed discussion of the basis of the interpretation, but the principal evidence may be summed up as follows.

At Todilto Park the Todilto limestone is overlain by a thick succession of rather distinctive sandstones which we believe resemble the sandstones of the Wingate, Navajo, and Entrada type more than they resemble those of the Morrison of east-central Utah. Directly above the limestone lie some 40 feet of soft, red, sandy beds, and above these about 100 feet of a hard, ledge-forming sandstone, very regularly bedded in horizontal layers alternately yellow and brownish red.

Along the road leading north from Highway 66 to Kit Carson's cave and Navajo Church, east of Gallup, sandstones that resemble those above the Todilto limestone at Todilto Park are overlain by beds that bear some resemblance to the Wanakah marl, and these in turn are overlain by a massive white sandstone that has some characteristics relating it to the Junction Creek sandstone.

We agree with the authors of *Professional Paper 183*²¹ in their identification of the Entrada at Beclabito (Biltabito) Dome, New Mexico and, therefore, like them, regard the limestone that, in places, lies on the Entrada there, as equivalent to the Pony Express limestone. But this limestone is directly overlain by approximately 70 feet of beds (those marked M in their Pl. 23A), that are very different from those overlying the Todilto limestone in Todilto Park, and that we incline to correlate with the Wanakah or Summerville (compare secs. 61 and 11, Pl. 2 of *Professional Paper 183*). The Entrada sandstone here is underlain by soft beds of the Carmel formation.

The lower part of the thick sequence of sandstones below the Carmel resembles the sandstone that overlies the Todilto limestone at Todilto Park. This sequence of sandstone at Beclabito Dome is underlain by a lenticular, thin, red and white limestone, that may be equivalent to the Todilto limestone at Todilto Park. We, therefore, agree with earlier workers in assigning the sandstone underlying the Todilto limestone at Todilto Park to the Wingate, but Gregory's²² original

²¹ A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Correlation of the Jurassic Formations of Utah, Arizona, New Mexico, and Colorado," *U. S. Geol. Survey Prof. Paper 183* (1936). See their sec. 11, Pl. 2, facing p. 16, and Pl. 23A, following p. 58.

²² Herbert E. Gregory, "Geology of the Navajo Country," *U. S. Geol. Survey Prof. Paper 93* (1917), p. 56.

FIG. 6.—Section at locality in McElmo Canyon, Colorado, designated by us as "Black Ledge," showing upper part of Entrada sandstone, lower part of Junction Creek sandstone, and beds between them.

identification of the overlying sandstone there with the Navajo seems to us more probable than the later interpretation²³ of this sandstone as a part of the Morrison, and of the Todilto limestone there as equivalent to the Pony Express limestone. We would, however, differentiate the 40 feet of softer, red, sandy beds between Todilto limestone and the color-banded sandstone at Todilto Park as perhaps equivalent to the Kayenta.²⁴

The sandstone overlying the thinly laminated beds (perhaps Wanakah or Summerville), in Plate 23A of *Professional Paper 183*, may be equivalent to the Junction Creek sandstone.

SECTION IN NORTHEAST CORNER OF NEW MEXICO

We consider it worth while to draw attention to beds exposed along the Dry Cimarron River²⁵ in the extreme northeast corner of New Mexico. We were led to examine these beds by R. P. Fischer of the Geological Survey, who mentioned their resemblance to the section at Uravan. The geologic map of New Mexico²⁶ shows only Trisassic and Morrison here. The section measured (Fig. 7) is on the northeast side of Route 64, 24.1 miles east of its junction with Route 73, where a nose of the redbeds comes down almost to the road and the sandstone directly above them is well exposed. This sandstone is the basal sandstone, bed *A*, of Figure 7. It is distinctly of Entrada type, and is apparently the one that Heaton²⁷ designates as Exter and correlates with the Entrada sandstone. As can be seen in Figure 7, the overlying section bears some resemblance to the section at Uravan. Many of the argillaceous beds have the sandy, concretionary character of the Wanakah marl; bed *B* resembles, in position and character, the carnelian sandstone; and bed *C* resembles the "green chert" zone. The lowest sandstone that we consider typical of the Morrison of east-central Utah is that at the top of the section. However, the green clay lenticles in bed *E* below this sandstone and

²³ Baker, Dane, and Reeside, *op. cit.* See especially p. 9, first paragraph under the heading "Morrison formation," and sec. 78, Pl. 2 facing p. 16; and compare with sec. 11, same plate.

²⁴ Cf. *Prof. Paper 183*, p. 5, under heading Kayenta formation.

²⁵ On some maps this is designated merely as Cimarron River. But there is another river by that name, a tributary of the Red River, in Colfax County, just at the west. Therefore, although the Cimarron River here referred to forms the headwater of the better known river by that name which flows through Oklahoma and southern Kansas, we follow the local usage in calling this the Dry Cimarron.

²⁶ N. H. Darton, "Geologic Map of New Mexico," *U. S. Geol. Survey* (1928).

²⁷ Ross L. Heaton, "Contribution to Jurassic Stratigraphy of Rocky Mountain Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 8 (August, 1939), pp. 1153-77. See especially Figure 7, section 43, p. 1166, and text pp. 1165-66.

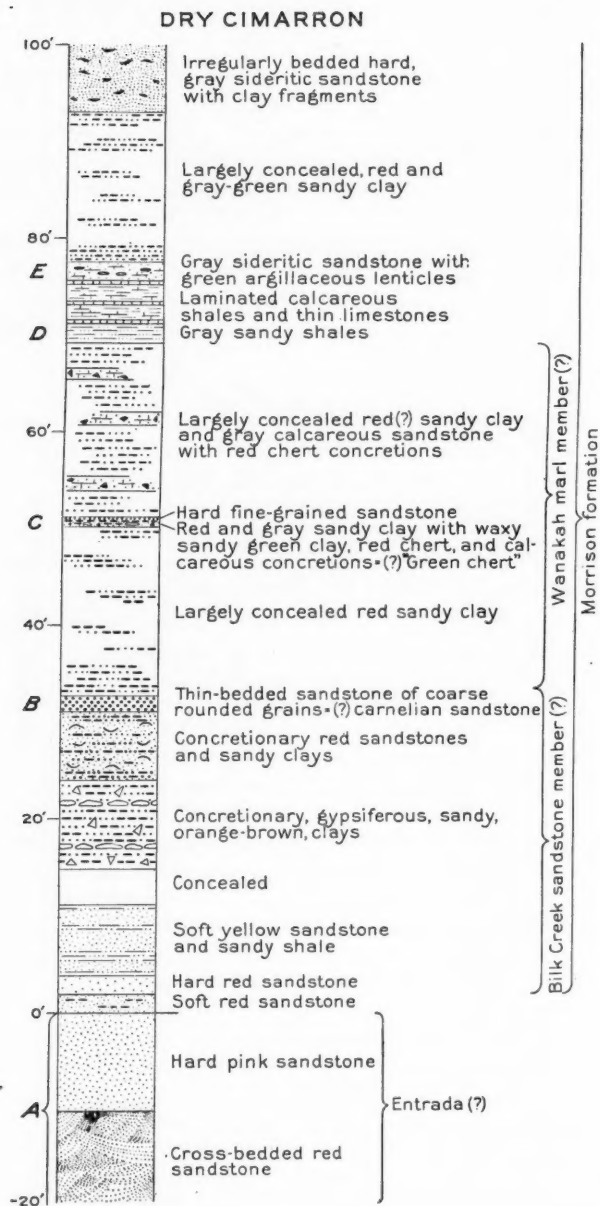
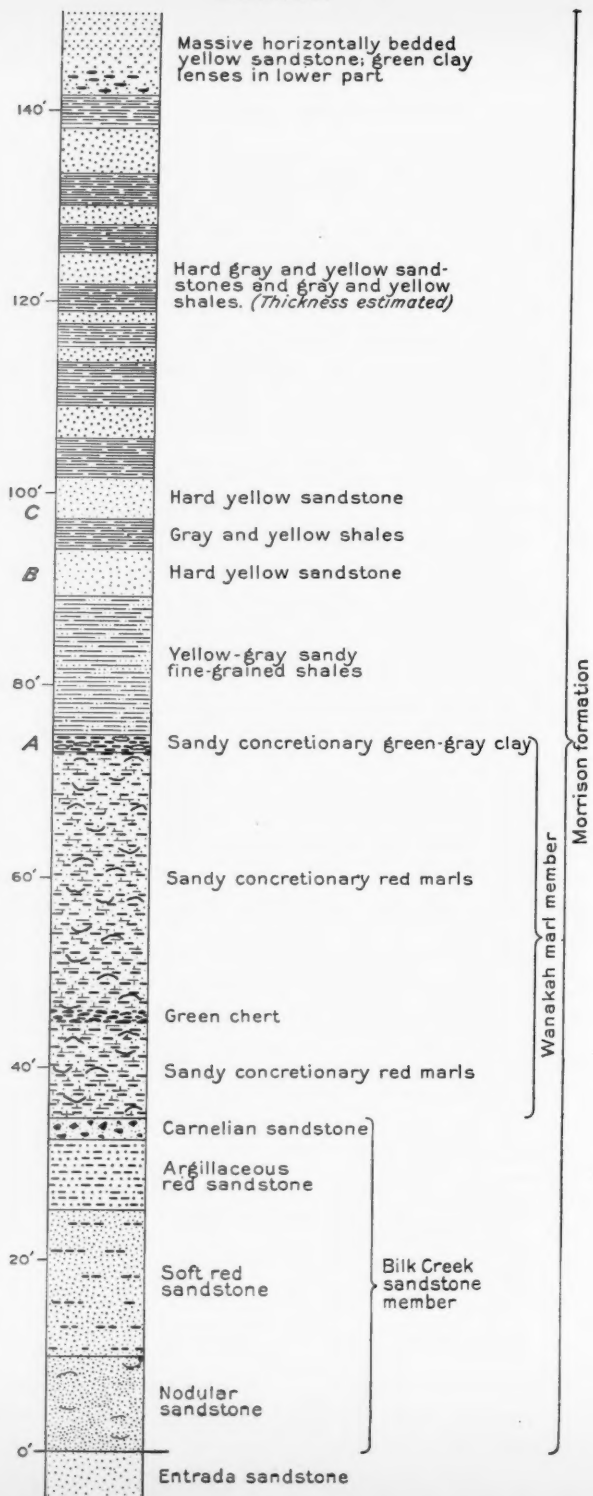


FIG. 7.—Section on Dry Cimarron River, northeastern New Mexico, showing tentative correlation with southwestern Colorado section.

DUNTON



the gray, sandy, shales of bed *D*, also resemble the basal Morrison beds of some sections. Thin limestones like those above bed *D* are also found at Uravan (Fig. 5) in beds that are probably younger than Wanakah. It seems likely, therefore, that the 40 feet or so of beds between *D* and *B* represent the Wanakah and the underlying beds, above bed *A*, the Bilk Creek sandstone.

The graphic section makes the difference between the upper 10 feet of bed *A* and the lower part of that bed appear more pronounced than it is, yet the possibility that this upper part should be included with the Bilk Creek sandstone should be considered.

RELATION OF NEW UNITS TO OVERLYING BEDS

Because we believe these several units in southwestern Colorado, previously assigned to the La Plata sandstone, are equivalent to beds underlying the basal Morrison of east-central Utah, we favor excluding these units from the Morrison of southwestern Colorado. Pending further studies in this area, however, they are all classed as members of the Morrison formation, but the feasibility of separating in this area a Morrison formation, thus restricted, from the underlying beds deserves special consideration.

The top of a thick, homogeneous, widely extended sandstone like the Junction Creek sandstone, representing a rise of base level and probably sub-aerial emergence, and lying approximately at the boundary between two distinct lithologic sequences, is likely, on theoretical grounds, to mark the exact boundary between these sequences. But in several places it is overlain by 20-30 feet of red, sandy marls resembling those of the Wanakah.

Where these upper marls, in turn, are overlain by massive, channel-bedded sandstone of mixed grain with coarse sand lenses and with clay fragments (generally green), a boundary can easily be drawn by accepting this sandstone as the base of the overlying sequence. Actually, a sandstone of this type, the Salt Wash sandstone member of the Morrison, has been regarded as the base of the Morrison formation in many places in Utah where it is more extensive. But genetic considerations make it improbable that the base of a formational unit would everywhere be occupied by such a sandstone, and the very

FIG. 8.—Section at Dunton, Colorado, showing upper part of Entrada sandstone and overlying beds. Green-gray clay at *A* is probably weathered layer at top of Wanakah marl. Beds shown above this are different from those that overlie Wanakah or Junction Creek at most localities in southwestern Colorado, and may be distinct intermediate series. All sandstones from *B* to top of section tend to weather brownish and are of type here termed sideritic. Beds above *C* form inaccessible cliff and thickness and character are estimated and generalized.

lenticular character of many of the sandstones of this type that lie at or near the base of the sequence overlying the Junction Creek sandstone is readily observed. In places such sandstones may lie at the base of a sequence or they may even be entrenched into deposits of the preceding sequence, in either position constituting a true basal bed there. At other places, however, they may be entrenched in earlier formed, finer-grained deposits of their own sequence, these finer-grained deposits intervening between them and the true base of the sequence. Such a condition is illustrated near the Galloway Ranch in McElmo Canyon where 13 feet of slightly sandy "purple" shales lie below channel-bedded sandstone and on 22 feet of red sandy marls of Wanakah type overlying the Junction Creek sandstone.

The differences between the more argillaceous beds of these two sequences, though not everywhere obvious, can, we believe, generally be recognized.

The fine-grained beds of Wanakah type are harder and more concretionary, and tend to break into chunky fragments with a more conchoidal fracture. Those of the younger sequence are more truly shaly.

In the fine-grained beds of the Wanakah, poorly sorted fine sand, with many grains surprisingly rounded for such fine-grained material, lies more or less disseminated in a waxy, argillaceous matrix. In the fine-grained sandy beds of the younger sequence the sand is more angular and the sand and clay are more intimately mixed.

In the younger sequence waxy clays or clay shales free of grit, which perhaps are altered fine volcanic ashes, are common; in the Wanakah they are very scarce.

The Wanakah marl is generally red whereas the argillaceous beds of the younger sequence are more generally "purple" and light green.

It may be that the Wanakah-like beds above the Junction Creek sandstone are transitional beds in the base of the later sequence and are due to the reworking of material from the Wanakah marl and the Junction Creek sandstone; but, as seen at the Galloway Ranch, the contact between the Wanakah type of marls and the younger shales seemed too sharp to accord with that interpretation.

In some places, where the typical, massive Junction Creek sandstone is absent, a sequence of beds typical neither of the Wanakah nor of the younger sequence, intervenes between the two. Characteristic of this intervening sequence are yellowish gray sandy shales and rather regularly bedded yellow sandstones that weather dark brown and that we have called sideritic. Such beds are present at Dunton (Fig. 8) and Section Point.

The beds overlying bed *A* at Uravan, as previously pointed out (Fig. 5), are also, in some respects, of an intermediate character, and bed *A* is of the sideritic type.

Whether these beds of intermediate type were deposited at the same time as the Junction Creek sandstone or represent a distinct member of the Morrison formation, perhaps peculiar to southwestern Colorado, remains to be determined. But, until they have been established as either one or the other, we recommend that they be grouped with the more heterogeneous upper sequence rather than with the well characterized Junction Creek sandstone or Wanakah marl.

WELL LOGGING BY RADIOACTIVITY¹

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ABSTRACT

Radioactivity logging is the only known method of making accurate lithologic records through the casing and cement. The radioactivity of the strata is determined by measuring the variations in conductivity produced by gamma rays in the gas in an ionization chamber contained in the subsurface instrument. It has been found that each formation tends to produce a curve of characteristic shape on the radioactivity logs, and that some of these characteristic curves are highly persistent laterally.

At present, the radioactivity logs are used chiefly to determine the position of the producing sands behind the casing, in order that the pipe may be perforated to drain them most effectively, and the process has been highly successful in this use. Other applications consist in determining the amount of sample lag, making correlations and cross sections, mapping subsurface structure for deeper drilling, and surveying potash deposits. A similar process may be used in making radioactivity surveys at the surface and in mines.

A method has also been developed for determining the radioactivities of cores and samples which has proved its value in interpreting the logs and in solving problems of sedimentation.

INTRODUCTION

The primary use of radioactivity surveys is to make accurate logs of cased wells. Since electric logging is a comparatively recent development, there are many thousands of producing wells, now cased and cemented, which have never been accurately logged. In many cases an accurate record of the formations in these wells is urgently needed in order to determine where to perforate the oil sands, and for correlation. Because electric logging is entirely limited to uncased holes, the only hope of securing the required data on these older wells lies in radioactivity surveys.

ACKNOWLEDGMENTS

The writer is indebted to S. A. Scherbatskoy, R. E. Fearon, B. Pontecorvo, G. Swift, J. L. Gartner, and R. L. Alder for information regarding the technical phases of the subject, and to these gentlemen and J. Neufeld, R. B. McCullar, and C. T. Casebeer for criticism of the manuscript. The cordial coöperation of many company geologists in supplying well logs and geological information is gratefully acknowledged.

PREVIOUS PUBLICATIONS

Three papers on well logging by radioactivity have been published previously. Westby and Scherbatskoy³ have given a brief description

¹ Presented by title before the Association at Houston, April 3, 1941.

² Geologist, Well Surveys, Inc.

³ G. H. Westby and S. A. Scherbatskoy, "Well Logging by Radioactivity," *Oil and Gas Jour.* (February 22, 1940), pp. 62-64.

of the theory of the process and its application to a correlation problem in Creek County, Oklahoma, and W. G. Green and R. E. Fearon⁴ have discussed in detail the theory and technical angles of the subject. It should be noted that these papers contain interesting radioactivity logs and correlation charts which are not included in the present paper. The writer⁵ has also published a brief description of the process.

The recent paper by Bell, Goodman, and Whitehead⁶ calls for comment, because their measurements show that the radium content of some sandstones is larger than that of the associated shales, whereas during the course of making radioactivity logs of about a million feet of strata, it has been found that pure sandstones and limestones almost invariably show less radioactivity than the shales. This apparent discrepancy is due to the fact that Bell, Goodman, and Whitehead measured only the radioactivity of the uranium series by means of alpha rays from radon, while in well logging the radioactivity of all substances is measured by gamma rays. Furthermore, since all but the hardest gamma rays tend to be absorbed before reaching the surveying instrument, it is chiefly these more penetrating rays which produce the log. Because the gamma rays from potassium are penetrating, and because potassium is much more abundant in shales than in sandstones and limestones, the shales on the radioactivity logs appear much more radioactive relative to limestones and sandstones than in the measurements of Bell, Goodman, and Whitehead.

DEVELOPMENT AND HISTORY OF PROCESS

The method of well logging by radioactivity was developed in the laboratories of Well Surveys, Inc., and Engineering Laboratories, Inc., as a result of a number of years of engineering research. From November, 1939, to May, 1940, experimental logs were made in a number of oil fields under the direction of J. L. Gartner, and he is responsible for first establishing the manner in which the common sedimentary rocks are expressed on the radioactivity logs. On May 1, 1940, the process was placed on a commercial basis. The Lane-Wells Company has been granted a license by Wells Surveys, Inc., to make radioactivity surveys in the United States, and at present has four units in operation. The Seismograph Service Corporation has been

⁴ W. G. Green and R. E. Fearon, "Well Logging by Radioactivity," *Geophysics*, Vol. V, No. 3 (1940), pp. 272-83.

⁵ W. L. Russell, "Well Logging by Radioactivity," *Oil Weekly* (November 11, 1940), pp. 16-21.

⁶ K. G. Bell, C. Goodman, and W. L. Whitehead, "Radioactivity of Sedimentary Rocks and Associated Petroleum," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 9 (September, 1940), pp. 1536 and 1538.

similarly licensed in South America, and operates a unit in Trinidad. Other parties will be placed in the field as soon as the equipment can be constructed.

PURPOSE OF THIS PAPER

Readers interested in the technical and engineering aspects of the subject are referred to the paper by Fearon and Green. The purpose of this paper is to supply information about the theory of the process, the operation of the instruments, and the interpretation of the logs needed by geologists using the method, to describe its various uses and applications, and to answer typical questions asked about it. Because of the newness of radioactivity logging, geologists are naturally less acquainted with its various phases than in the case of the older well-surveying methods; consequently, a more detailed explanation seems advisable.

RADIOACTIVITY

A brief description of radioactivity should give a better understanding of the process. Radioactivity is the spontaneous change of the atoms of one element into those of another. The rate of this change is generally expressed as the "half-life," which is the time it takes for half of any quantity of an element to change into another element. The half-life of the various radioactive elements varies all the way from a fraction of a second to more than 10 billion years. It is a characteristic property of each radioactive element, and none of the ordinary geologic agencies, such as heat and pressure, are able to change it in the least.

During the course of their transformations, the radioactive elements give off three different types of rays. The alpha rays consist of atoms of the rare gas, helium, which are expelled at velocities of several thousand miles per second. The beta rays are electrons, which are expelled at velocities approaching the speed of light. Gamma rays are also produced during the course of the radioactive processes. They are electromagnetic waves like light waves, but of much smaller wave length. While the wave length of visible light is about one fifty-thousandth of an inch, the wave length of gamma rays is about one ten-billionth of an inch. Gamma rays are very much like X-rays, but they are of shorter wave length and more penetrating. The gamma rays alone are used in making the radioactivity surveys.

Most of the radioactive elements belong to one of three different series. Each series starts with a parent element, which changes into another element, that in turn changes into a third element, *etc.* The uranium-radium series starts with uranium and includes as one of its

intermediate products the well known element, radium. The actinium series starts with actino-uranium, while the thorium series starts with thorium. Potassium is also radioactive, but its product undergoes no further change. The gamma rays used in radioactivity surveys are produced chiefly by the members of the uranium-radium and thorium series, and by potassium. After about 100,000 years the elements of the various radioactive series are in equilibrium with each other, and then the percentage of any element in a series can be calculated if the proportion of one member present in a rock is known.

DISTRIBUTION OF RADIOACTIVE MATTER IN ROCKS

It has been found by careful tests that all the natural rocks contain measurable quantities of radioactive material, though it is generally present in extremely minute amounts. Of the igneous rocks, the light colored acidic types like granite contain most, while the heavy, basic rocks contain least. The radioactive matter in the sediments was originally derived from the igneous rocks, but it was very unequally distributed among the different types of sedimentary deposits, as Figure 2 shows.

DESCRIPTION OF APPARATUS

The instrument used in radioactivity well surveying consists of a metal cylinder about 9.75 feet long and 3.625 inches in diameter. The lower part contains a gas under pressure, and is known as the ionization chamber. The gamma rays from the formations surveyed ionize the gas in the ionization chamber, and decrease its resistance to the passage of an electric current. The conductivity of the gas is proportional to the intensity of the gamma rays; thus, the current passing through the ionization chamber indicates the relative amounts of radioactive material in the formations surveyed. The current is produced entirely by the batteries in the instrument, and is not generated by the radioactive substances themselves.

The variations in the amount of current passing through the ionization chamber amount to only one ten-trillionth ($1/10,000,000,000,000$) amperes. This current is amplified enormously in the instrument, and is sent up to the surface through a co-axial cable, which is a cable containing a conductor of electricity on the outside and inside, with insulating material in between. The same cable is used to lower and raise the instrument in the well. As the cable reaches the surface it passes over a measuring wheel, which is connected to an arrangement of Selsyn motors that registers the exact depth at the well, in the winch truck, and in the instrument truck. The current is conducted from the

end of the cable in the winch or hoist truck to the instrument truck, where after further amplification, it operates an automatic pen recorder which draws the log in the field while the survey is in progress. It is a great advantage to be able to see the log immediately, in order to be sure that the proper sensitivity is used. Figure 1 shows the dis-



FIG. 1.—Field set-up, with measuring wheel in foreground. Dark box at left of measuring wheel is Selsyn transmitter, which indicates depth of surveying instrument, and is synchronized with Selsyn receivers that also indicate depth in winch truck at left and instrument truck at right.

position of the apparatus during a survey. As the instrument is lowered into the well, it may stick temporarily on deposits of paraffine or salt. This would produce variations in the tension on the cable, or even an accumulation of slack cable, with consequent errors in depth measurements. As a result, greater accuracy is obtained by logging coming out of the well. The normal speed of surveying varies from 1,500 to 2,000 feet per hour.

LABORATORY TESTS OF SAMPLES

Well Surveys, Inc., has also developed an apparatus for testing the radioactivity of cores and samples in the laboratory, the best results being obtained with samples weighing 0.75 pound or more. It has been found that these laboratory measurements of radioactivity give valuable assistance in interpreting the gamma-ray logs. Because so many of the wells surveyed either have no lithologic log at all, or one in which the recorded depths are untrustworthy, the relative radioactivities of some rocks which are rare or which occur in thin beds can not be determined from the gamma-ray logs alone. Consequently, it is necessary to rely on laboratory determinations to ascertain how these rocks would be expressed on the radioactivity logs.

In addition to furnishing data on the general interpretation of the records, the laboratory tests indicate the type of log and the value of the data which would be obtained by radioactivity logging in a given area. For example, the sample tests will show whether there is enough contrast in radioactivity between various formations to enable them to be differentiated on the radioactivity logs, and whether the various strata are of uniform radioactivity or show variations which would be useful for correlation.

EFFECT OF MATERIALS IN HOLE

One of the advantages of gamma-ray logs is that the materials likely to be found in oil wells have no unfavorable effect on the logs. The radioactivity survey is just as satisfactory whether the well contains air, natural gas, oil, fresh or salt water, or mud fluid. The logs can be made in cased and uncased holes with equal accuracy, and satisfactory surveys can readily be made through three strings of casing and the intervening cement. Of course, the cement and casing cut out some of the gamma rays, but this effect can be neutralized by increasing the sensitivity of the instrument. However, the best practice involves keeping the same sensitivity on at least one curve throughout the log of each well, with a separate curve for any part that may be run with increased sensitivity.

If the cement is very thick and weakly radioactive, the log shows a shift to the left at the base of the cement, followed by a more gradual shift to the right at its top. In such cases, the position of the top of the cement behind the casing can be estimated from the log. However, in most cases, the effect of the cement is so weak that its top can not be determined. If the cement has about the same degree of radioactivity as the formations surveyed, its effect is merely to decrease the amplitudes of the apparent variations in radioactivity, which means that the curves or projections to the right and left are smaller.

The absorption of some of the gamma rays by the casing and cement prevents the use of an absolute scale of radioactivity on the logs. A graphic decimal scale of absolute gamma ray intensity could readily be used on the logs, but it would not be exactly proportional to the radioactivity of the rocks behind the casing, because of the varying absorption in the casing and cement. Such an absolute scale is, of course, not necessary, because the relative intensities of radioactivity given on the logs are sufficient for all practical purposes. The best interpretations of gamma-ray logs are made by comparing the patterns of the various formations with the parts immediately above and below, and not with distant parts of the same log.

The effect of cosmic rays on the surveying instrument appears to be negligible below a depth of 50 feet.

PREPARING WELL FOR GAMMA-RAY LOGGING

All that is necessary to do to prepare a well for radioactivity surveying is to remove the rods and tubing, and check the casing record to be sure that the hole is large enough for the instrument to enter it. With the present-size instruments, the smallest size of casing which the instrument can enter is $4\frac{1}{4}$ -inch A.P.I. If the hole is clogged with deposits of paraffine or salt, it may be necessary to clean them out with some heavy tool before making the survey. Some suspending medium is needed for lowering the instrument into the well, but if there is no derrick or mast, the instrument can be suspended from a gin pole on a truck backed up to the well, or from a temporary wooden frame.

ACCURACY OF MEASUREMENTS

The accuracy of the depth determinations to the various formations on the radioactivity logs depends on the elimination of two different sources of error: inaccuracies in the depth-recording instruments, and uncertainties in the interpretation of the graphic logs. Errors of the first type have been corrected by comparing the depths read from the Selsyn motor with accurately established depths in a well. One way of estimating the size of the errors due to the interpretation of the records is by logging the same section several times and noting any discrepancies in the depths of the contacts indicated. When this is done, it is found that the depths of the contacts established from different runs at the same speed do not differ by more than one or two feet.

If the log were made while the instrument was resting on the bottom of the hole, the result would be a nearly vertical line with no irregularities except for statistical fluctuations. After the instrument was

lifted off the bottom, irregularities in the curve due to differences in the radioactivity of the rocks traversed would begin to appear on the log, and the contrast between the smooth line made while the instrument was on bottom and the irregular curve produced while it was ascending past different rock types might be marked enough to enable the depth of the bottom of the hole to be estimated fairly closely. However, the vertical line produced while on bottom would ordinarily be difficult to distinguish from the curve made by a rock of uniform radioactivity, and the depth of the well can therefore be determined much more accurately by the weight indicator attached to the measuring wheel than by the inspection of the radioactivity logs.

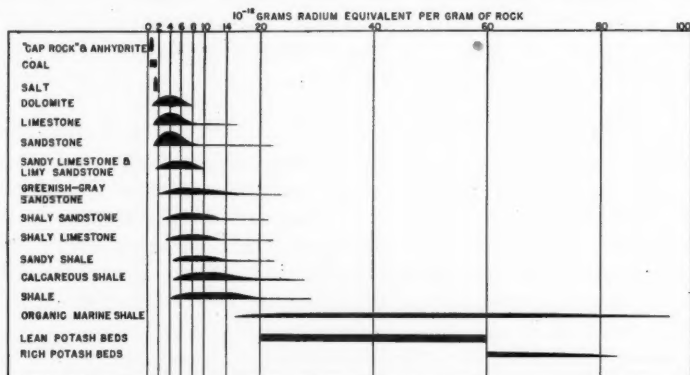


FIG. 2.—Diagram showing relative radioactivities of various sedimentary rocks, as indicated by intensity of their gamma-ray radiation. Vertical width of lines increases with frequency of occurrence, and intensity of radioactivity increases toward right. Radioactivity of common occurrences of a rock is therefore shown by thick part of lines, radioactivities corresponding with thin parts of lines being rare. Units of measurement indicated at top of figure show total intensity of gamma rays from all sources, expressed in terms of amount of radium per gram of rock required to produce same intensity; hence, these figures do not indicate amount of radium actually present. Relative radioactivities of various rock types are based on radioactivity logs; therefore they are well established, but figures for intensity are based on insufficient number of determinations, and may be changed considerably by future work.

INTERPRETATION OF GAMMA-RAY LOGS

IDENTIFICATION OF ROCK TYPES

The manner in which the various rock types are expressed on the radioactivity logs can best be illustrated by a graphic representation, as in Figure 2. In this figure, the relative positions of the various rocks are the same as in the radioactivity logs, that is, the radioactivities increase toward the right. The position of the lithologic types in Figure

2 is determined partly by their expression on the radioactivity logs, and partly by the results of laboratory tests of the radioactivities of samples made by B. Pontecorvo and others of the research department of Well Surveys, Inc.

The distinction between rocks occupying the same position in Figure 2, as is the case with sandstones, limestones, and dolomites, must be made by correlating the gamma-ray log with a lithologic log in the region.

FLUID CONTENTS

At present it is not possible to determine from the gamma-ray logs the nature of the fluid contents of the various reservoir rocks. However the logs show accurately the tops of the various oil-producing formations, and from their structural position with reference to other tests of the same reservoir rocks it is often possible to predict before perforating whether they will contain oil, gas, or salt water.

ESTIMATING PERMEABILITY AND POROSITY FROM RADIOACTIVITY LOGS

The curves and patterns shown on the gamma-ray logs are not directly related to permeability, as are the self-potential or "porosity" curves on electric logs. However, in some cases the permeability may be estimated from the radioactivity logs. This is possible where the formations consist solely of shales and uncemented sandstones. In such formations the permeability of the sandstones is determined chiefly by the amount of shaly material in them, and, since the shaly materials are more radioactive than the pure sands, the farther the log shifts to the left, the more permeable the rock. In strata of this type, the gamma-ray logs and the self-potential curves on the electric logs are in almost perfect agreement. If, however, the sandstones are in part cemented by lime or silica, there will not be much difference on the radioactivity logs between the permeable part and the cemented part. In other words, while the maximum on the electric log would cover only the porous section of the sandstone, the maximum on the gamma-ray log would extend over the whole of the sandstone. The radioactivity logs will, however, show minor shale breaks, only a foot or two in thickness, in the sandstones. These show as small, sharp peaks at the right on the larger leftward projections due to the main body of the sandstone.

Well D, on the right-hand margin of Figure 3, illustrates the similarity of the radioactivity logs and the self-potential curves on the electric logs in sections consisting chiefly of porous sandstones and shales. However, in the part of well D shown in Figure 3, there are some calcareous and chalky beds which show in a different manner on the

two types of logs. The limestones and dolomites occurring in shales produce a peak at the left on the radioactivity logs, while on the self-potential curves of the electric logs they ordinarily produce only a small peak at the left unless permeable. In comparing electric and radioactivity logs, it should be remembered that the electric logs should indicate the formations approximately 6 or 8 feet deeper, because they were made before the removal of the rotary bushing and table.

The estimation of porosity and permeability of limestones and dolomites from gamma ray logs is much more difficult than is the case with sandstones. It is not possible to determine from the gamma-ray logs alone which parts of the limestones are porous. However, if the porous parts of a limestone formation have been determined in some wells of a field, gamma-ray logs of these wells may show how the variations in porosity affect the radioactivity log. Once this relation has been established, it may hold for all the wells in the field for that particular producing horizon. Even if the variations in radioactivity associated with the higher porosity are very minute, they may be logged accurately by lengthening the time constant of the instrument and surveying very slowly. Unless the porosity relations for a limestone or dolomite producing formation have been previously determined in this manner, it is not safe to attempt to estimate the porosity from radioactivity logs.

STATISTICAL FLUCTUATIONS

The intensity of the gamma rays affecting the instrument at a given depth in a well is not constant, but fluctuates slightly, owing to variations in the number of atoms that chance to disintegrate in a given moment. This situation may be understood by imagining a cloud of fireflies flashing at irregular intervals on a summer night. The number of flashes in a second would vary greatly, owing to chance, but the percentage of difference in the number of flashes per hour, due to the chance irregularities, would be much smaller. In the same way, these chance variations in radioactivity known as statistical fluctuations produce very large variations in the intensity of the gamma rays during extremely small time intervals. These changes in intensity become progressively smaller with longer time intervals, because the irregularities of short duration tend to approach a fixed average.

If the automatic pen recorder reacted instantaneously to the alterations in gamma-ray intensity, it would dance over the paper in a rapid succession of peaks and lows which would have no marked relation to the radioactivity of the formations surveyed. This effect is eliminated by the time constant in the instrument, which is a device

for averaging the variations over suitable time intervals. The time constant on the newer radioactivity-surveying instruments may be altered simply by turning a dial. When surveying at a speed of 1,500 feet an hour, the ionization chamber is affected by each thin stratum of rock for about 10 seconds. The time constant should, therefore, be adjusted to average the irregularities over approximately this length of time. If, on the other hand, the speed of the survey were reduced to 300 feet per hour, the time constant could be five times as long.

Although, as explained, there are difficulties in using an absolute scale of radioactivity on the gamma-ray logs, an absolute standard of gamma-ray intensity is easily established. This is accomplished by placing a bottle holding approximately 17 grams of pitchblende containing about 21 per cent U_3O_8 against the middle part of the ionization chamber. With the sensitivity commonly used at normal speeds, this produces a deflection of about 4 inches on the graphic logs, while the deflection due to the change from normal shale to pure sandstone or limestone would be about 1-1.5 inches. The statistical variations on the same scale produce errors of about 0.2 inch.

Because statistical fluctuations are not large enough to affect the interpretations under normal conditions, the need for considering them arises only when the sensitivity of the instrument is increased. It is advisable to use this increased sensitivity in logging weakly radioactive rocks, strata in which the contrasts in radioactivity between the various formations are slight, and in recording parts of wells in which a large percentage of the gamma rays is cut out by abnormal thicknesses of casing and cement. Since any decrease in the intensity of the gamma rays causes an increase in the relative size of the statistical variations, the errors they produce are more serious where the cement is thicker. However, it should be understood that it is only where the cement is of distinctly abnormal thickness that the effect of its absorption of the gamma rays becomes important.

If the sensitivity is increased without changing the speed or the time constant, the apparent size of the statistical fluctuations is amplified by the same amount. For instance, if the deflection of the bottle test in the foregoing example were enlarged from 4 inches to 20 inches, by a 5-fold increase in sensitivity, the statistical variations would amount to 1 inch instead of 0.2 inch, provided that the speed and time constant remained the same. Reducing the speed does not change the amplitude of the statistical fluctuations. Hence, a 5-fold reduction in the speed would not diminish the size of the swings to the right and left due to the statistical variations, but would cause them to occur five times as frequently in the same vertical distance on the log, and

to average one-fifth as wide vertically. If the sensitivity were greatly increased and the time constant correspondingly lengthened without decreasing the speed, the instrument would not remain opposite the thinner strata long enough to log them accurately. Consequently, this set-up should be used only where the geologic formations to be logged are thick, and it is not important to record the thinner beds.

It should be obvious from the foregoing that the only way to log with increased sensitivity without sacrificing accuracy is to lengthen the time constant and decrease the speed. If this is done, the variations in radioactivity can be magnified to any desired degree with no loss in accuracy. The size of the statistical fluctuations, although not directly affected by changes in speed, is related to the speed because of the connection between the speed and the time constant. Hence, the rule may be made that the size of the statistical variations is proportional to the sensitivity, inversely proportional to the square root of the time constant, and directly proportional to the square root of the speed.

The statistical fluctuations should, of course, be carefully differentiated from permanent changes in radioactivity. It is probable that no permanent changes in radioactivity large enough to show on the radioactivity logs occur during the life of an oil field in those parts of the subsurface strata which are sealed off from the wells by the casing and cement. Where there is no cement behind the pipe, slight changes in the radioactivity curves might be produced during the course of time by the settling of the mud fluid, or by the circulation of water in the annular space between the casing and the rock, in the rare cases where such circulation occurs. However, the effects of settling and water circulation behind the casing should be negligible unless the water deposits a precipitate. Deposits precipitated on the inside of the casing by the oil-field waters may, of course, produce an effect on the logs.

The statistical variations have been treated at some length, because they seem to be one of the most likely sources of error in the interpretation of gamma-ray logs, in spite of the fact that these errors may be easily eliminated by the proper procedure. This situation arises partly because this subject is more abstruse and less easily understood than the other aspects of the process, and partly owing to the fact that, because the need for considering the effect of statistical variations arises only occasionally, it is easily neglected or forgotten. Furthermore, if this subject is not understood, field crews might be expected to increase the sensitivity without making a corresponding decrease in the speed.

The preceding discussion of statistical fluctuations should assist in

understanding the great advantages of an ionization chamber over a Geiger counter in well logging. It is chiefly the size of these statistical errors which limits the speed of surveying. Since the magnitude of the statistical errors is reduced by absorbing a larger percentage of the total quantity of the gamma rays passing through the instrument, the greater the percentage absorbed, the faster the well can be logged with an equal degree of accuracy. The researches which have been made in the laboratories of Well Surveys, Inc., indicate that an ionization chamber is much more efficient in absorbing gamma rays than a Geiger counter of the same dimensions. This difference in the absorption efficiency is so large that if the gamma-ray logs were made with Geiger counters instead of ionization chambers, it would take approximately three to five times as long to obtain the same degree of accuracy.

SURFACE RADIOACTIVITY SURVEYS

The same general methods used in surveying wells can be used to make radioactivity surveys at the surface. Fortunately, the surface surveys are much more rapid as well as cheaper than the subsurface logging. The speed of surface gamma-ray recording should be approximately 6,000 feet per hour.

The possible uses of surface radioactivity surveys are too numerous to describe in detail in this paper, but a few of them may be mentioned. In cases where the formations logged in wells come to the surface, it may be of advantage to correlate the subsurface formations with their outcrops. If there is doubt as to whether a certain formation known at the surface is found in drilling, radioactivity surveys of both the surface and subsurface strata may solve the problem. Furthermore, radioactivity profiles across the outcrops should indicate the type of log and degree of correlation which would be found in the same formation underground.

The surface radioactivity surveys may evidently be recorded in two different ways. One method would be to measure a profile across the strike of the formations, and plot this up in the form of a stratigraphic section or geologic column, allowing for the angle of dip. In this form the different radioactivity surveys of the same strata could be correlated with each other or with the well logs. Another method would be to plot the radioactivity profile on a horizontal scale along the traverses made, disregarding the dip. This type of radioactivity survey could be used to detect faults and formation contacts, and to map outcrops of veins, dikes, and igneous intrusions, which are likely

to differ considerably in radioactivity from the surrounding rocks. Since it seems likely that the weathered products of different types of rocks would differ considerably from each other in radioactivity, radioactivity surveys may be of especial value in areas of deep weathering.

The success of radioactivity surveys in correlating subdivisions of thick, apparently uniform formations has already been mentioned. The same methods could be used on rocks of this type at the surface, where they may be of assistance in structure mapping, through the use of variations in radioactivity as key horizons.

Surface radioactivity surveys may also be useful in finding deposits of metallic ores, some of which are radioactive in themselves, or are associated with rocks of abnormal radioactivity.

USES OF GAMMA-RAY LOGS

GUN-PERFORATING

The most obvious use of gamma-ray logs is to determine where to gun-perforate the casing, and most of the surveys have been made for this purpose. In cases where there are no reliable logs of the well surveyed, it is necessary to correlate the gamma-ray log with the sample log of some well in the vicinity, in order to identify the formations and to differentiate between the sandstones and limestones. Generally, the geologic units stand out so clearly on the radioactivity logs that a geologist thoroughly familiar with the stratigraphy of the area can identify the formations immediately.

The advantages gained by using gamma-ray logs in connection with perforating are that the sample lag is eliminated, and the operator is enabled to select only the most promising parts of the oil or gas sands for testing. This should lessen the dangers of encountering flows of salt water, with resultant expensive squeeze jobs. The radioactivity logs also show the shale breaks in the producing sands, and other details which are helpful in devising the best perforating programs. The improved knowledge of the structure of the oil sands made possible by the accurate formation tops and correlations given by the gamma-ray logs should greatly assist in determining which sands are oil- or gas-producing, and which parts of the producing sands are water-bearing. In oil fields which produce from several different oil sands, the accurate knowledge of the structure and correlation of these sands secured through gamma-ray logging will assist in determining the position of the fluid contacts and in predicting how they will migrate during production.

RESULTS OF PERFORATING ON BASIS OF GAMMA-RAY LOGS

The results of perforating the casing on the basis of radioactivity logs have in general been highly satisfactory. In scores of wells, production varying from 100 to 1,000 barrels of oil per day has been found, and the list of such wells is steadily growing. For example, the gamma-ray log of a well in North Texas showed several sandstones. The casing was perforated opposite one of these and the well flowed 900 barrels of oil per day.

DETERMINING SAMPLE LAG

One of the most useful aspects of radioactivity logs is their ability to measure accurately the amount of sample lag. The methods commonly used to make sample logs consist in sifting the samples out of the mud fluid and plotting their character against the depth at which the well was drilling when they reached the surface. Since it may take considerable time for the samples to reach the surface after they have been cut by the bit, the depths shown on the sample logs are greater than the true depths by the distance the well drilled during this interval. This error is called sample lag. At present it is customary to correlate the speed of drilling with the sample log, and when this can be done accurately, sample lag is eliminated. However, since this is a recent development, there is a vast number of older wells in which the amount of sample lag is unknown, and can only be determined accurately by radioactivity logs.

COMBINATION OF GAMMA-RAY AND SAMPLE LOGS

When a good sample log is plotted alongside a gamma-ray log, the amount of sample lag is immediately apparent; generally it varies from 1 to 50 feet. In many cases it is possible to draw nearly parallel lines slanting down from the formations on the radioactivity log to the same horizons on the sample log.

It is evident that sample logs and gamma-ray logs together are much more useful than either alone. The radioactivity logs show accurately the depths of the various formations, and the details of the shale breaks, which even the best sample logs commonly fail to reveal. Many of the samples on which the sample logs are based are so contaminated by cavings from higher up the hole that the character of the rock penetrated may be obscured. However, the annular space between the casing and the walls of the hole is so thin that the cavings which may fill it ordinarily have only a negligible effect on the radioactivity logs. Hence, the inaccuracies due to cavings are largely eliminated by gamma-ray surveys.

On the other hand, sample logs give the lithologic interpretation of the patterns shown on the gamma-ray logs, and in some cases indicate the nature of the fluid contents of the reservoir rocks penetrated. It is of interest to note that radioactivity logs show that, if the operators had gun-perforated the casing at the depths where the best available data (including sample logs) indicated the oil sands were present, they would in some wells have missed them entirely.

Gamma-ray logs are especially useful in the rather numerous wells where oil occurs in the top of the oil sand, with salt water below. In such wells, perforating without accurate logs would result in expensive squeeze jobs due to encountering salt water in the lower parts of the oil sand, but by the use of radioactivity logs the operators are enabled to hit the exact top of the oil sand in almost every case.

MAPPING SUBSURFACE STRUCTURE

Although previously most of the gamma-ray logs have been made in order to determine where to perforate the casing, this is by no means the only use of the process. In fields where the available logs are poor, it may be impossible to construct reliable structure maps. However, by making radioactivity surveys through the casing in these fields, it should be possible to map the structure accurately. The improved knowledge of the structure obtained in this way should be of value for selecting locations for deep tests, for finding lateral extensions of the production from the present producing formations, and for finding similar structures elsewhere. The radioactivity logs also measure the variations in the intervals between the stratigraphic horizons above the producing sands, and these variations may serve to date the time of origin of the folding or compaction which generated the producing structures. By studying these interval variations and the other stratigraphic and structural information revealed by the gamma-ray logging, it may be possible to determine the nature and mode of formation of these structures. Radioactivity logs may, of course, also be used to determine where faults intersect the wells.

RADIOACTIVITY CROSS SECTIONS AND THEIR USE IN STRATIGRAPHIC AND STRUCTURAL RESEARCH

In many areas it is possible to combine a number of radioactivity logs into a cross section which illustrates the main structural and stratigraphic features with remarkable clearness. For example, gamma-ray logs of the salt domes which have overhang, as at Barbers Hill, Chambers County, Texas, show plainly the projecting tongue of salt with its overlying anhydrite cap rock. Figure 3 is an example of a cross section through the Urbana pool, Arkansas. Both Figure 3 and Figure 4

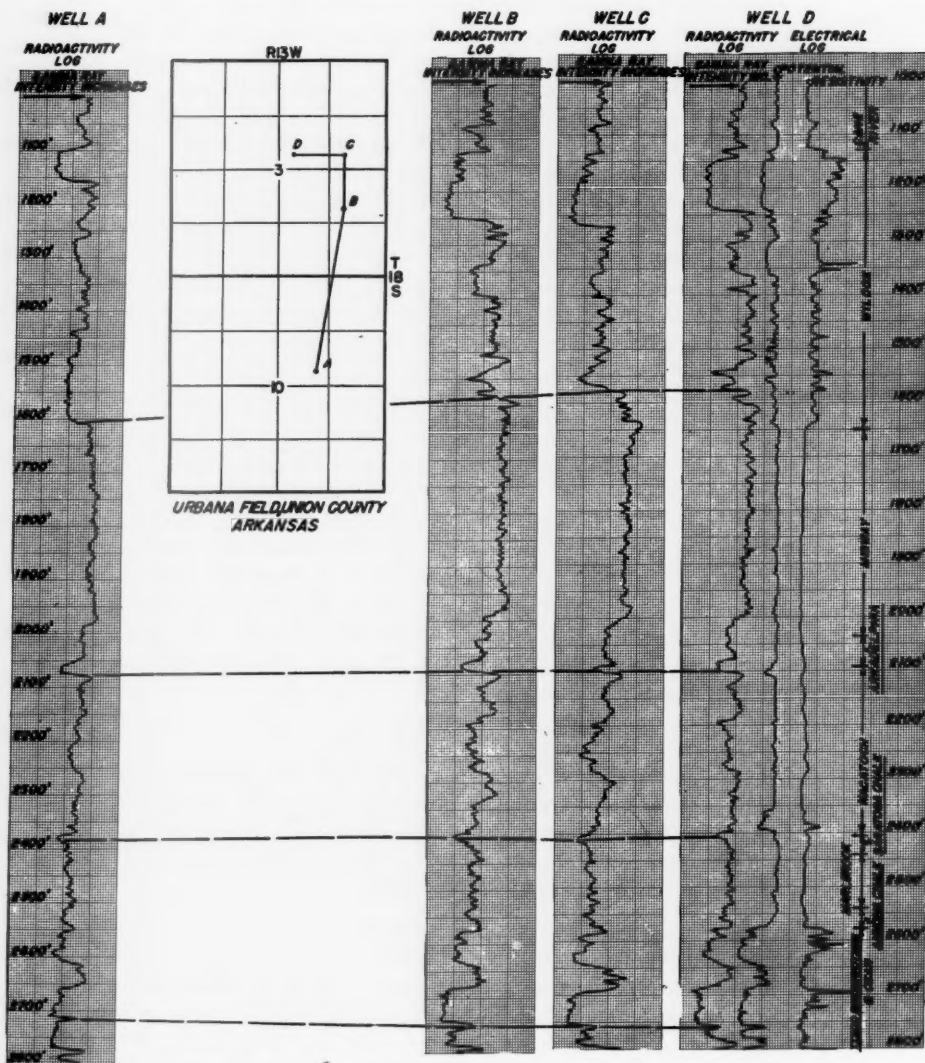


FIG. 3.—Radioactivity cross section through Urbana pool, Union County, Arkansas, showing at right a comparison of gamma-ray and electric logs of same well. Electric log has been elevated 6 feet in order to allow for removal of rotary table and bushing.

are arranged to bring out the stratigraphy and not the structure—that is, a level line follows a certain stratum, not an elevation above or below sea-level. Figure 4, though it consists of only two logs, is a good illustration of the way in which radioactivity logs may be used in stratigraphic and structural work. Well C, which has the shorter intervals, is located higher on the great Permian dolomite reef which forms the producing structure in the Cooper pool and in many other oil fields of the area. Geologists are naturally interested in discovering to what extent these structures are produced by anticlinal folding, and how much of the apparent uplift is due to the compaction of the sediments around the projecting reef. The solution of such problems is obviously important in deeper drilling, as well as in stratigraphic and

TABLE I
(All figures in feet)
CORRELATIONS, ELEVATIONS, AND INTERVAL CHANGES OF PERMIAN BEDS BETWEEN
TWO WELLS IN COOPER POOL, LEA COUNTY, NEW MEXICO, SHOWN IN FIGURE 4

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>
<i>Depth of Bed</i>		<i>Elevation of Bed</i>		<i>Column C</i> <i>Minus</i> <i>Column D</i>	<i>Loss of</i> <i>Interval</i> <i>in Well C</i>	<i>Thickness of</i> <i>Interval in</i> <i>Well B</i>
<i>Well C</i>	<i>Well B</i>	<i>Well C</i>	<i>Well B</i>			
1,047	1,020	2,240	2,255	-15	—	—
1,180	1,172	2,107	2,103	4	19	152
1,558	1,574	1,729	1,701	28	24	402
2,280	2,323	1,007	952	55	27	749
2,957	3,052	330	223	107	52	729

structural research. Figure 4 proves that radioactivity logs in this area will indicate the correlation, interval changes, percentage of shale and other rocks and structural position of the Permian strata above and flanking the reefs. These are just the facts needed to determine the time of origin of the structures, and to decide to what extent they are due to folding or compaction. Table I illustrates the manner in which the logs may be used in structural and stratigraphic work. It is evident that the two logs in the Cooper pool alone go a long way toward solving the problem of the relative amounts of folding and compaction which have produced the structures.

Column E of Table I shows how much higher structurally the beds were found in well C than in well B. Evidently well C runs lower structurally than well B in Permian strata above the Rustler anhydrite and much higher than well B for strata in the lower part of the same series and upper part of the "Big lime." The total thinning of the intervals in well C as compared with well B is 122 feet between a depth of 1,020 and 3,052 feet.

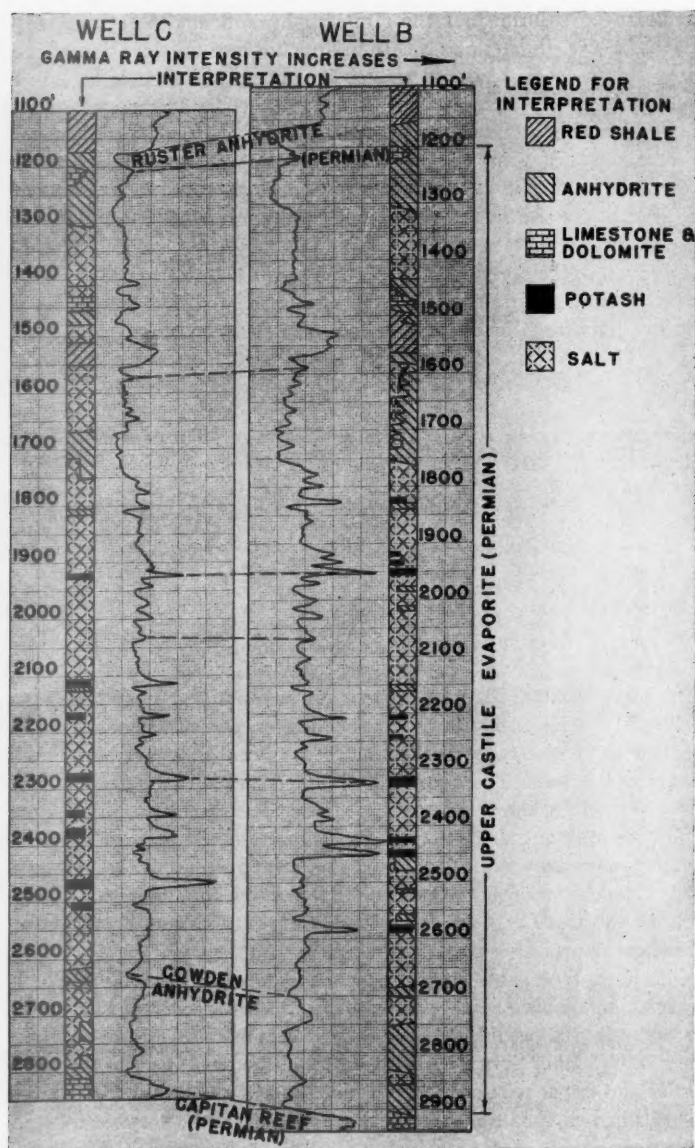


FIG. 4.—Radioactivity logs of two wells about $\frac{1}{2}$ mile apart in Copper pool, Lea County, New Mexico, showing correlation, interval changes, and expression of potash beds.

USE OF GAMMA-RAY LOGS FOR CORRELATION

It is probable that gamma-ray logs will eventually be used extensively for correlation. Since the radioactivity of the strata changes

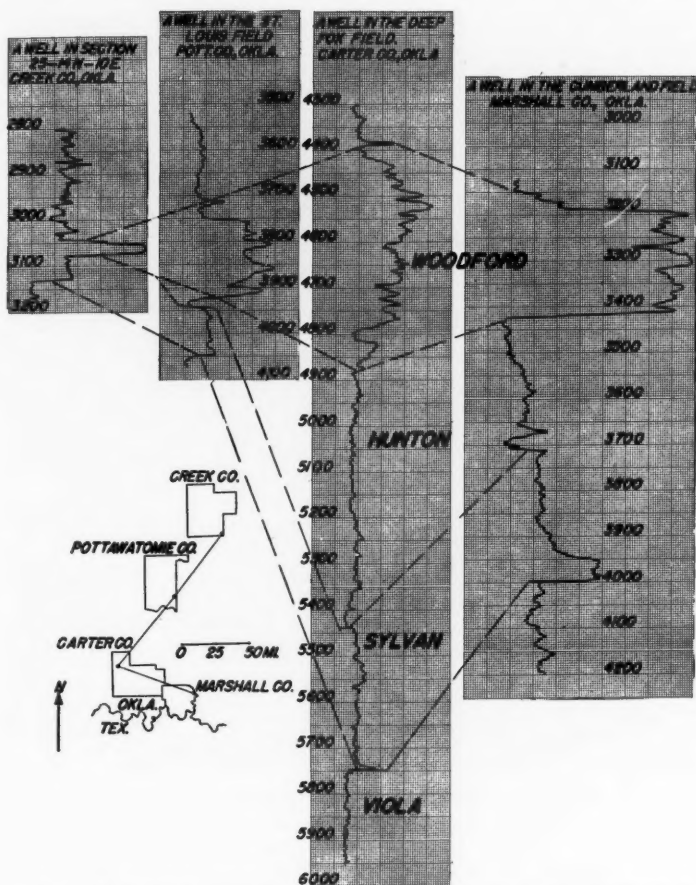


FIG. 5.—Radioactivity logs of wells in Creek, Pottawatomie, Carter, and Marshall counties, Oklahoma, illustrating correlation of logs across long distances.

with the lithology rather than following the time units, the distances over which the radioactivity logs may be correlated will depend on the persistence or lenticularity of the various rock types, as is the case with lithologic and electric logs. Fortunately, the different geologic formations tend to make characteristic curves on the radioactivity

logs, and these characteristic shapes are about as persistent as the lithologic units they represent. Some formations, such as the Woodford, or Chattanooga, show in the same manner on the radioactivity logs for distances of more than 500 miles, and the appearance of the Viola, Sylvan, Hunton, and Chattanooga is so similar over much of Oklahoma that they may be recognized at a glance. This is brought

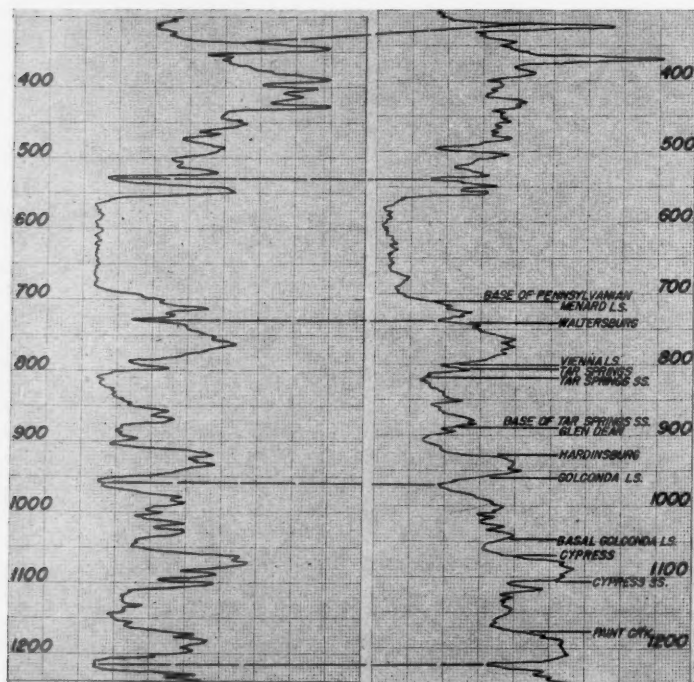


FIG. 6.—Correlation of radioactivity logs of two wells about $\frac{1}{4}$ mile apart in Cordes pool, Washington County, Illinois.

out by Figure 5 which illustrates the correlation of gamma-ray logs across long distances. The direction in which this section was taken happens to be the one in which the thicknesses and character of the formations change most rapidly. It is evident that, in spite of the marked changes in thickness, the formations are still readily recognizable. In many areas the gamma-ray curves of the same formations are strikingly similar over considerable areas, even minor details being faithfully reproduced on a series of logs, as is illustrated in Figure 6.

PRE-CRETACEOUS SEDIMENTS IN CORDILLERA ORIENTAL OF COLOMBIA¹

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ABSTRACT

Although there are scattered references in the literature to exposures of rocks of Paleozoic age in the Cordillera Oriental of Colombia, the fact that they are widespread and probably represent a good portion of the upper Paleozoic has not generally been recognized. This paper describes briefly several hitherto unpublished localities, and points out that the extensive phyllites and possibly even the schists of the Cordillera are of Paleozoic age.

There has been confusion between the Cocuy series of Cretaceous age and the similar Girón series of pre-Cretaceous age, which series has until recently been considered Cretaceous. This paper points out that the Girón series may be observed in many places resting on Paleozoic strata, and is disconformably overlain by Lower Cretaceous beds. The Girón is not present in the eastern half of the range.

The Cocuy series, on the other hand, is present only in the eastern part of the range, and seems to be equivalent to the limestones and shales of Lower and Middle Cretaceous age of the western part.

PALEOZOIC SEDIMENTS

The existence of fossiliferous Paleozoic sediments southeast of Bogotá was noted by Hettner (1)³ who called them the Quetame series. Fossils from this series have been collected at several localities and have been determined to be Carboniferous in age (2).

At Floresta (Boyacá) is a soft shale whose abundant fossils, discovered by A. A. Olsson and Teófilo Ramirez in 1935, are believed by Kenneth E. Caster (3) to have a boreal aspect and to be of Onondagan (lower Devonian) age. It seems possible that this formation was mistaken for Tertiary by Robert E. King (2) who reported a Fenster in a flat overthrust at Floresta. The writer saw no clear evidence of flat, alpine type overthrusting in the Cordillera. Great upthrusts are common, and there is one just west of the town of Santa Rosa (Boyacá) but the section eastward to Floresta appears to be normal, and includes Tablazo limestone and shale (Middle Cretaceous), La Paja shale and Rosa Blanca limestone and shale (Lower Cretaceous),⁴ the Girón series on the east slope of the ridge, the Floresta beds (Devonian), and near Corrales, metamorphic rocks with igneous intrusions. The actual contact between the Girón and Floresta

¹ Manuscript received, January 16, 1941. Published by permission of the Tropical Oil Company.

² Pennsylvania Topographic and Geologic Survey.

³ Numbers in parentheses refer to bibliography at end of article.

⁴ The beautifully developed Cretaceous strata in the Cordillera Oriental of Colombia have never been adequately described or defined in published articles. A complete description of the Cretaceous by the geologists of the Tropical Oil Company is in preparation, and it is hoped, will be published in the near future.

beds was not observed, but there was no reason to believe that it was faulted.

On the west side of the Magdalena Valley near Nare and Puerto Berrío (Antioquia) is a dark shale series containing plant remains. Graptolites have been reported from a black shale series somewhat farther west (4), but recent searches have failed to confirm them.

Along the road between Bucaramanga (Santander) and Bocas, fossiliferous Paleozoic beds are exposed between Río Suratá and Bocas. These beds were discovered in 1937 by Phillip Merritt. In conformity with his as yet unpublished work, it is proposed that the lower fossiliferous series from Río Suratá to Puente de Tierra be called the Suratá series, and the higher, less fossiliferous series from Puente de Tierra to Bocas be called the Bocas series.

The Suratá series consists of brick red shale with beds of fine quartzite, at least one bed of hard bluish limestone, and hard bluish gray shale and sandy shale. It is fossiliferous throughout its entire thickness. The limestones contain crinoid stems, and the shales contain bryozoans, pelecypods, gastropods, and brachiopods including spirifers and productids. No description of the forms has been published to date.

The total thickness of the series could not be determined in the time available for its study, since both eastern and western edges of the belt appear to be faulted. The series dips easterly, and was interpreted as the east flank of an anticline, isolated on both sides by faults. On the east are gneisses, intruded by granodiorites and pegmatites. The series may be intruded by quartz-porphyry at Puente de Tierra.

The Bocas series extends westward from Puente de Tierra to below Bocas, dipping toward the west. It apparently is higher in the section than the Suratá series and appears to underlie the Girón. Its thickness was not exactly determined, but it appears to range from 500 to 1,000 meters. It consists principally of black and dark brown shale with thin beds of limestone. In the lower part it also contains some fine hard brown sandstone, characterized by small cubes of limonite after pyrite. The shales are highly carbonaceous in places, and there are a few thin beds of coal. The latter are metamorphosed and penetrated by thin beds of calcite. Fossils are exceedingly scarce. A few poorly preserved gastropods were noted, and the coaly beds contain plant fragments. At its top, one kilometer below Bocas on the railroad, is fine brown sandstone with small cavities, on which the Girón appears to lie conformably.

A series of limestones, black shales, and thin sandstones is exposed in the Cerros de Múcura, 7 kilometers east of Totumal, a small village

6 kilometers southeast of Aguachica (Magdalena). It appeared to be quite devoid of fossils. It is associated with the Girón, and probably underlies it, but the structure is so exceedingly complex that the contact relations could not be worked out. The same series apparently passes east and north of Carmen (Norte de Santander).

Phyllites probably Paleozoic in age are found in numerous localities. They are well exposed south of Bucaramanga where they are intruded by quartz porphyry. At the Meseta de Los Santos the Girón appears to overlie the phyllites, but the contact may be faulted. West of Soatá (Boyacá) the Girón lies on a thick phyllite series which has been intruded by quartz porphyry and granodiorite.

More intensively metamorphosed sediments underlie large areas in the Cordillera Oriental, and they have been intruded by granodioritic rocks. Highly metamorphosed mica schists are found underlying the Floresta beds east of Floresta, northeast of Aratca (Santander), west of Pamplona (Norte de Santander), and are exposed for 40 kilometers along the west front of the Cordillera north of the Río Lebrija. It seems possible that they are also Paleozoic in age.

On the accompanying map (Fig. 1) the Quetame, Floresta, Suratá, and Bocas series are shown by vertical ruling, and the metamorphosed sedimentary series by horizontal ruling.

GIRÓN SERIES

A thick redbed series has long been recognized as a stratigraphic unit in the Cordillera Oriental. It was named the Girón series by Hettner (1), who ascribed it to the Cretaceous. No fossils of any kind have been found, to the writer's knowledge, in strata undoubtedly belonging to this series in Colombia. Most writers on Colombian geology have continued to place the Girón in the Cretaceous, although what is undoubtedly the same series has long been recognized in Venezuela as pre-Cretaceous. This error probably arose from a confusion of the Girón with the stratigraphically higher Cocuy quartzite, although Hettner recognized them as distinct units.

A recent article by Victor Oppenheim (5) correctly notes the distinction between the Girón and Cocuy series, and suggests that the Girón be placed in the Jurassic on the basis of some fossils found in Venezuela (6). The article fails, however, to define accurately the upper and lower limits of the series.




Lithologically the Girón is a typical redbed series consisting of massive red and green sandstones and conglomerates, with red and green shales. It is best exposed in the gorge of the Río Lebrija along the railroad between Bucaramanga and Puerto Wilches. Unfortu-

MAP OF NORTHERN
CORDILLERA ORIENTAL
REPUBLIC OF COLOMBIA

Showing Distribution of Girón Series

0 10 20 30 40 50 60 70 80 90 100 KILOMETERS

LEGEND

- Giron Series 
- Paleozoic 
- Probable Paleozoic 

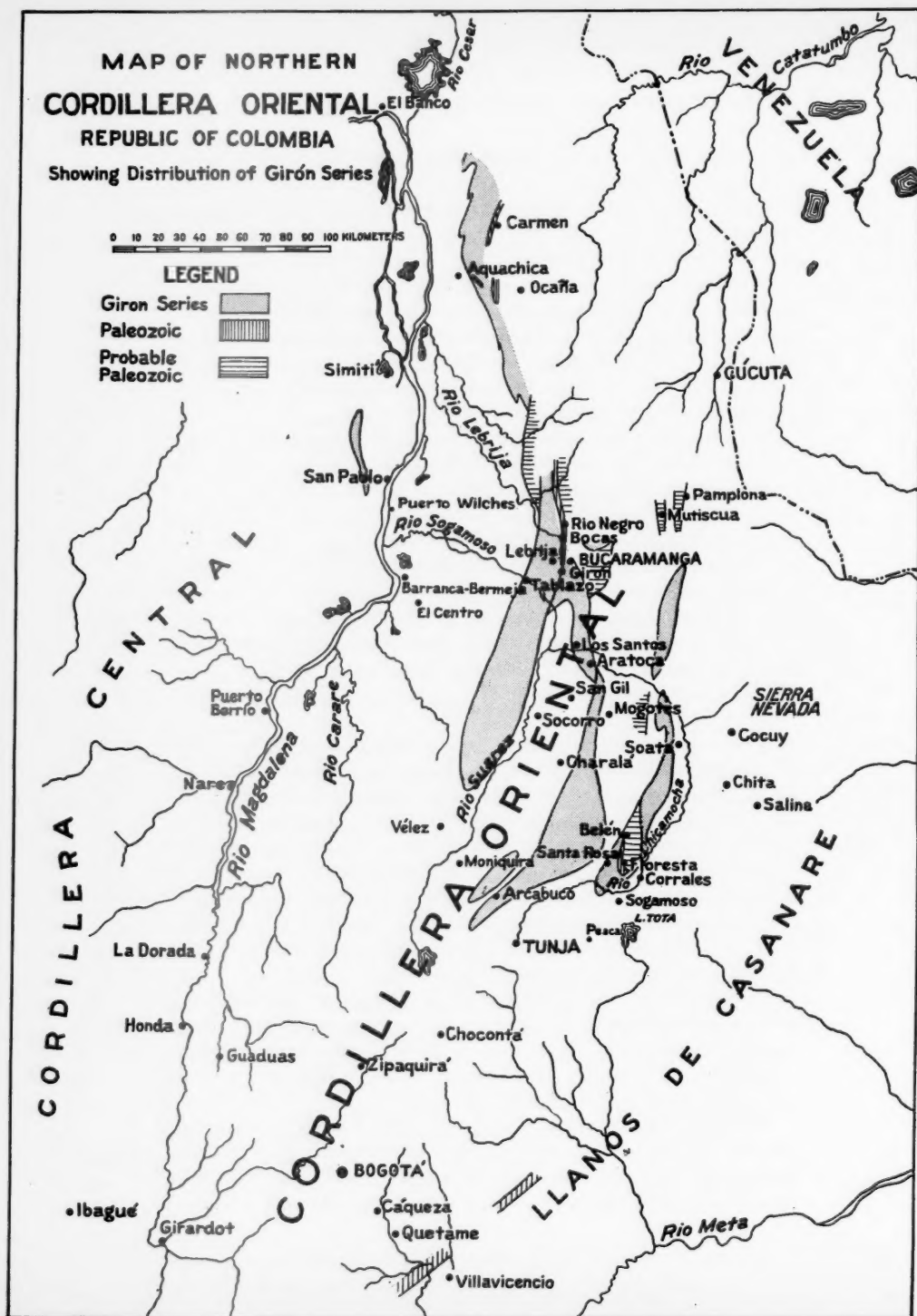


FIG. 1

nately, it is somewhat faulted there, so that its thickness can not be accurately determined, but is not less than 1,000 meters.

Near Bocas the base lies on non-fossiliferous shales and sandstones of the Bocas series. The basal part consists of hard quartzitic coarse conglomerate. The pebbles are subangular white quartz, mostly less than 2 inches in diameter. There are also beds of hard brown shale and fine sandy greenish shale. Higher in the section brick red shale beds become common. The middle of the series consists of hard bluish quartzite and shale, with both conglomerates and redbeds missing. The upper part consists of coarse white and bluish quartzite with beds of brick red shale and sandy shale.

At the Meseta de Los Santos, 24 kilometers southeast of Bucaramanga, the basal Girón is underlain by brick red shales containing lenticular beds of tuff with fragments and pebbles of porphyry. It is not clear whether they belong with the Girón or the underlying, probably Paleozoic phyllites.

Elsewhere in the Cordillera Oriental the Girón shows the same lithologic characteristics and is easily recognizable. It is a prominent mountain-forming bed in the western half of the range. South of the Río Lebrija gorge is a plateau underlain by soft and deeply weathered Girón, which rises toward the south and forms the jagged Cordillera de Lloriquies as far as Vélez (Santander) where the Girón plunges beneath the Cretaceous. The valley of the Río Suarez east of this range is underlain by flat and slightly faulted Cretaceous beds, bounded on either side by faults. East of Charalá the Girón reappears, and forms the high range between Charalá and Santa Rosa. It is also exposed, flanking the Paleozoic and metamorphic beds at Floresta, in the hills between Santa Rosa and Corrales.

The Girón forms the greater part of the west front of the Cordillera north of the Río Lebrija. This great escarpment marks a fault where the older rocks are thrust against the Tertiary beds of the Magdalena valley. The older rocks consist of Cretaceous, Girón, Paleozoic, and acid intrusives, folded and faulted in an exceedingly complex manner.

In this region the Girón contains enormous sills of porphyries, for the most part acidic, apparently quartz porphyries and granophyres. Individual beds may be several hundred meters thick, and they occupy perhaps half of the section. These sills have not been differentiated from the Girón on the accompanying map.

The Girón is also found in numerous places along the west side of the Magdalena valley between Puerto Wilches and Simití, where it dips gently toward the east. It appears to rest on the igneous, but the contact was not observed by the writer. It is missing at Simití, where

the basal Cretaceous rests directly on andesites. South of Puerto Wilches the Girón is not found, and the Tertiary rocks for the most part rest on the basal rocks of the Cordillera Central in transgressive overlap. Contrary to most published work on Colombian geology, there is no evidence of faulting on the west side of the Magdalena valley from Ibagué to El Banco.

The Girón is thus younger than upper Paleozoic, and underlies Lower Cretaceous beds. It must be between Permian and Jurassic in age and may well be Jurassic as suggested by Oppenheim.

LOWER CRETACEOUS

The Lower Cretaceous of the Magdalena valley region, as exposed at the west front of the Cordillera Oriental in the gorge of the Rio Sogamoso above Tablazo, consists of the Rosa Blanca limestone and La Paja shale. The names were proposed by O. C. Wheeler in 1929 and have been used by the geologists of the Tropical Oil Company. Both formations are abundantly fossiliferous, the Rosa Blanca being especially characterized by echinoids and the La Paja by a small ammonite. The fauna has been studied by A. A. Olsson, and is Neocomian in age.

The Rosa Blanca rests concordantly, on the Girón at Tablazo, 10 kilometers farther north at Santa Isabel, and in the Lebrija gorge. At the latter place the basal Cretaceous consists of a conglomerate of large rounded Girón boulders, followed by normal Rosa Blanca limestone.

In the central part of the Cordillera the writer has observed Rosa Blanca lying on Girón near Nobsa, north of Sogamoso (Boyacá), at Arcabuco (Boyacá), and between Santa Rosa and Floresta. At the last locality the Rosa Blanca is deeply weathered and is yellowish shale, full of echinoids. On the west side of the Magdalena valley the contact between the Rosa Blanca and the Girón may be seen west of San Pablo (Bolívar) where both formations are concordant and dip gently east.

Although there is undoubtedly a disconformity between the Girón and Cretaceous, there was no angular unconformity at any of these localities, and the Cretaceous seems to have partaken of all the deformation which the Girón has suffered.

MIDDLE CRETACEOUS

The writer does not wish to discuss the Cretaceous, which is well developed in the Cordillera Oriental, but would like to add something to the discussion of the Cocuy sandstone by Victor Oppenheim (5).

The Cocuy sandstones are definitely of Cretaceous age and are found only in the eastern half of the range. They appear to be the equivalent of the middle, and in places also the lower, part of the Cretaceous shales and limestones of the western part of the Cordillera. This was first recognized by A. A. Olsson, who found fossils characteristic of the Tablazo limestones of Middle Cretaceous age in the Cocuy sandstone at Alto las Cruces, west of Pesca (Boyacá). The writer has never noted limestone below the Cocuy series, except possibly between Chipaque and Cáqueza, southeast of Bogotá. Oppenheim suggests that the Cocuy series overlies limestone at La Mesa. He quotes Scheibe (7) and Karsten (8) as having found Neocomian fossils in the Cocuy series east of the Páramo de Chita, and at Cáqueza. The Cocuy series apparently thickens toward the east, and it seems likely that in the eastern part of the range it includes the lowermost Cretaceous.

The Girón series is not found in the eastern half of the Cordillera where the Cocuy series is well developed, and this fact has probably given rise to the confusion of the two series.

Between Cáqueza and Quetame (Cundinamarca), southeast of Bogotá, the Cocuy lies on a thick, unfossiliferous black shale series, which in turn overlies the fossiliferous Paleozoic Quetame phyllites. East of Chita the Cocuy lies on the same black shale series. Olsson and the writer considered this series to be Lower Cretaceous, but it is possible that it is Paleozoic in age and equivalent to the Bocas series.

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GEOLOGICAL NOTES

PHOTOGEOLOGY¹

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The introduction of aerial photographs to exploration geology—both petroleum and mining—approximately 15 years ago was the most significant advance in the science since the advent of the plane table. The use of aerial photos in geological exploration was retarded by a failure to recognize their latent possibilities and to consider them as maps. These two factors combined with an apparent high cost were sufficient to discourage their use by many individuals and organizations.

In petroleum exploration the aerial mosaic has found some usage as a base map for horizontal control primarily in geophysical programs. From the geological point of view this application seems most uneconomic, especially where either surface geology or the surface expression of subsurface structure is present. This statement is made because of the fact that an aerial photograph is a precise surface geological map. Although the photographs lack the symbols and elevations found on a conventional map they do portray all of the surface geological features in their exact relationships.

The geologic interpretation of aerial photographs is based on a thorough background of field geology combined with a study of the photographs in the field. For this little known branch of geology the writer suggests the term "photogeology," which is defined as the geologic interpretation of aerial photographs. A photogeologic map would be a map produced from a stereoscopic study of the aerial photos.

It was only after several years of surface mapping with aerial photographs—using them as a base on which to plot geological observations and concurrently studying them stereoscopically—that the value of this method was fully appreciated. The field geologist who was fortunate enough to work with contact prints was thus able to view his surface work in the third dimension and interpret the geomorphology of the region in the light of actual field determinations. Thus the various inexplicable features depicted on the photographs by slight monochromatic shadings assumed definite values and the

¹ Manuscript received, June 4, 1941.

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various outcrop, vegetation, and stream patterns suggested structural interpretations ordinarily overlooked.

An advance in the technique of using aerial photos was made when the normal process of field mapping was reversed. That is, instead of first mapping the geology in the field and then studying the area stereoscopically, a photogeologic map was made in the office. This map indicated all of the visible cartographic units, inclination of beds when and where ascertainable, faults, drainage patterns, watersheds, and in general all geologic, geomorphologic, and cultural features. The results of this method were interesting and gratifying. It proved that a trained photogeologist could produce a map which would agree very favorably with actual field observations. It further revealed that in studies of this nature certain data were indicated that were either overlooked or were not visible in the field. The geomorphologic interpretations made through a third dimensional study were invaluable in arriving at structural conclusions that could not have been determined otherwise. Finally, photogeology proved itself the most economic method of rapid geological reconnaissance yet developed. By this method the outstanding anomalies of a region could be quickly and accurately located and the evaluation of these anomalies in the field could proceed without the delay occasioned by detailed geophysical or geological exploration.

The basic background for photogeology is a comprehensive training in field geology as has already been indicated. However, of equal importance is a working knowledge of geomorphology—a subject that has received little attention from the undergraduate and geologist alike. The lack of interest in this subject has been due partly to a deficiency of literature on the subject and its apparent lack of economic application. The classic works of William Morris Davis should be required reading for any student of photogeology. The recent work of Lobeck,³ profusely illustrated with many excellent photographs and block diagrams, is outstanding and can well serve as a guide in this study.

The interpretation of aerial photographs considers not only land forms and obvious geologic units but also the effects caused by variations in reflecting power of soils and rocks of exactly similar colors, the habit and density of vegetation, drainage patterns, the distribution and pattern of cultivated lands, railroads, quarries, reservoirs, and other cultural features. The presence of thick vegetation, as in tropical countries, does not entirely preclude the possibility of making some observations or interpretations. However, it is evident that those

³ A. K. Lobeck, *Geomorphology*. McGraw-Hill Book Company, Inc.

regions that are covered by loess, wind-blown sand, glacial deposits, snow, ice, or any other surficial mantle will reveal no more geology than can be observed on the surface.

The application of photogeology to exploration work should be considered as an aid rather than an end. It has been argued that in areas of good exposures aerial photos are unnecessary and in regions of no outcrops they are of no value. Such reasoning is specious. For example: in the swamps of the Gulf Coast of the United States—a region noted for its lack of topographic expression and surface geology—salt domes have been interpreted as anomalous areas from the photographs by the drainage patterns surrounding them. Mud volcanoes in dense tropical jungles have been readily interpreted from the photographs by a "timber halo." Ancient stream channels, filled by younger deposits, both in jungle and desert regions are expressed on the photos by vegetation and soil changes. Kelp adhering to the offshore submarine outcrops of the Monterey shale delineates the Elwood anticline off the Santa Barbara, California, coast and is clearly discernable on the aerial photographs. The intersection of transverse faults in the Mother Lode district of California, indicating points of rich mineralization, stand out clearly on the aerial photographs but are difficult to locate and observe in the field. The pattern and strike of the pegmatite veins in the San Gabriel Mountains of southern California are at once apparent from the pictures. Innumerable examples could be cited where no surface geology or cartographic units are visible in the field but where ample data are present on the photographs to make sound deductions and interpretations.

The production of a photogeologic map has several variations all of which are personal preferences in expressing the interpretations on paper. The only essential equipment is some type of stereoscope for viewing the photos in the third dimension. There are many types of stereoscopes and the matter of choosing one is governed by personal preference and the cost. With some practice it is possible to view a stereo pair and observe the third dimension without the aid of any instrument.

The contact prints are the regular 7×9-inch prints made by direct contact printing from the aero film. Contact prints should overlap at least 60 per cent on the sides and 30 per cent on the ends to give full stereoscopic coverage. The scale of these prints is usually about one inch equals 1,650 feet and it requires about 50 of these overlapping prints to cover adequately one township.

One method of making a photogeologic map is to outline and accentuate directly on the photos the pertinent features while viewing

them stereoscopically. For this purpose an appropriate system of colors and symbols is used. When the area has been completely studied the data are traced from the photos to some suitable transparent material, thus producing a map of the entire area. Another method, which is essentially the same, traces off the data on a transparent strip while the photos are studied stereoscopically, thus leaving the pictures clean when the process is completed. The scale of the finished map will conform to the scale of the photos.

In regions of poor surface geology, insufficient subsurface control, and unreliable geophysics the use of photogeology as a solution to the problem of isolating anomalous areas for detailed investigation has been successful and economical. There are many regions in the United States that have been mapped in the past by excellent field geologists but a re-examination of many of these areas by photogeology will undoubtedly reveal new facts and interpretations of economic significance.

EXPLORATION FOR EVAPORITE SALTS IN GREEN RIVER BASIN, WYOMING¹

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The discovery during 1938, in Sec. 2, T. 18 N., R. 110 W., Sweetwater County, Wyoming, of a substantial body of "evaporite salts" by the Mountain Fuel Supply Company while drilling an exploratory test for oil on the Blacks Fork anticline, 15 miles west of the town of Green River, called the attention of the chemical industry to a new source of raw material which might eventually be of national importance. This discovery, although of greater interest to the economic geologist than to those interested in petroleum work, must be credited to the vigilance of those in the latter profession.

The Mountain Fuel Supply Company cored numerous thin strata of evaporite salts, and one bed, at a depth of 1,590 feet, which was approximately 16 feet thick. Stringers of the "salts," as well as isolated crystals, were first noted about 300 feet below the top of the Green River formation, and indications continued to the base of this formation, which has been determined as being approximately 1,155 feet thick. W. T. Nightingale, geologist, who first noted these salts, forwarded samples of the material to H. I. Smith, chief, mining division, conservation branch, United States Geological Survey, and a subse-

¹ Manuscript received, June 13, 1941.

² Exploration department, Union Pacific Railway, 422 West Sixth Street.

quent chemical analysis made by R. C. Wells of the Survey found this material to be nearly pure trona ($\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$). Joseph J. Fahey, United States Geological Survey, Washington, D. C., also studied core material, and discovered a new mineral of carbonate of sodium and calcium which he called shortite.³

Sodium-base chemicals, including sodium carbonate, sodium bicarbonate, and sodium sulphate, are produced by several methods in the United States. These include the operation at Trona, San Bernardino County, California, which is unique in that it utilizes the brines occurring in a crystal body at Searles Lake, and the use of salt-bearing waters in Michigan and on the Gulf Coast. The Green River deposit is of particular importance in that it may be amenable to mining by methods similar to those applied to the removal of potash ores near Carlsbad, New Mexico.

Core drilling during 1940 has outlined a body of trona of minable thickness in an area of approximately 12 square miles, but exploration at this date has not extended a sufficient distance toward the center of the basin to determine what the maximum development of the crystal body may be.

³ *Amer. Mineralogist*, Vol. 24 (1939), pp. 514-18.

RESEARCH NOTES

RELATIONSHIP OF CRUDE OILS AND STRATIGRAPHY IN PARTS OF OKLAHOMA AND KANSAS¹

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Crude oils of similar composition are found in 37 Burbank sand pools situated in a curving belt of country 10-20 miles wide and 150 miles long in southeastern Kansas and northeastern Oklahoma (Fig. 1). This conclusion is based on data obtained in a recent investigation of the composition of crude oil made by the research committee of the Tulsa Geological Society, a subcommittee of the American Association of Petroleum Geologists. During the past 6 years this committee has studied the analyses of crude oils from several Paleozoic zones ranging from the Arbuckle limestone to the Permian sands in eastern Oklahoma and eastern Kansas. In the course of the investigation approximately 500 analyses have been considered, and the results reported in this paper represent only a small part of the total data studied. The similarity in the composition of crude oils in the Burbank sand (Pennsylvanian) throughout this large area is noteworthy, as the preliminary findings on crude oils from several other producing zones in Oklahoma and Kansas indicate that as a rule crude oils from different pools show considerable variation in composition. These data on the composition of the crude oils from Burbank sand pools are presented briefly in advance of the publication of a detailed report on the crude oils from several producing zones in a large area of Oklahoma and Kansas.

COMPARISON OF CRUDES

In the investigation of crude oils of Oklahoma and Kansas, only analyses made by the United States Bureau of Mines Hempel method have been used. In this method 15 fractions are isolated at temperature intervals of 25° C. The crude oils have been compared by the correlation-index method⁸ developed during the investigation. This method employs a simple index number based on the boiling point-specific gravity relationships of pure hydrocarbons. The magnitude of the correlation index indicates certain character-

¹ Manuscript received, July 14, 1941. Published by permission of the directors of the United States Geological Survey and the United States Bureau of Mines. The writers are members of a committee of the Tulsa Geological Society, a subcommittee of the research committee of the American Association of Petroleum Geologists.

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⁷ Chemist, United States Bureau of Mines, Bartlesville, Oklahoma.

⁸ H. M. Smith, "Correlation Index to Aid in Interpreting Crude-Oil Analyses," *U. S. Bur. Mines Tech. Paper 610* (1940).

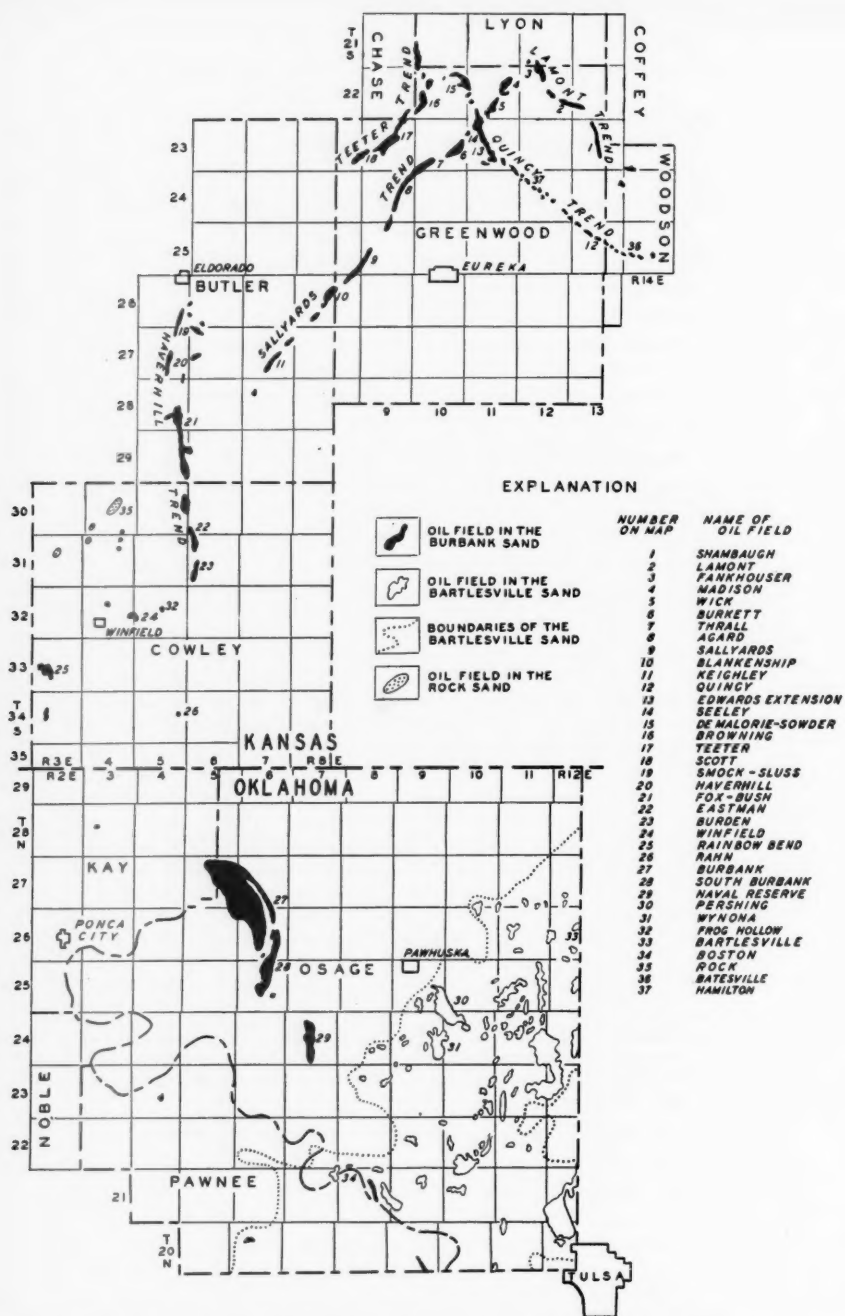


FIG. 1.—Map showing location of Burbank sand pools in southeastern Kansas and northeastern Oklahoma.

TABLE I
AVERAGE CORRELATION-INDEX NUMBER AND OTHER FACTORS OF ANALYSES OF CRUDE OILS FROM BURBANK SAND

Fraction (or Cut) Number	Distillation at Atmospheric Pressure								Vacuum Distillation at 40 Millimeters					Crude Oil			Residuum	
	3	4	5	6	7	8	9	10	11	12	13	14	15	A. P. I. gravity of crude	Sulphur content of crude, per cent	Carbon residue of crude, per cent	Residuum, per cent	A. P. I. gravity of residuum
Distillation temperature, °C.	75°-100°	100°-125°	125°-150°	150°-175°	175°-200°	200°-225°	225°-250°	250°-275°	Up to 200°	200°-225°	225°-250°	250°-275°	275°-300°					
Lamont trend, aver- age of 5 analyses	15.6	18.0	20.0	22.2	24.6	26.0	28.0	29.6	33.6	35.0	37.4	39.4	42.0	39.6	.19	1.8	20.7	17.6
Quincy trend, aver- age of 13 analyses	16.5	19.3	21.0	23.0	25.0	26.5	28.0	29.5	33.0	33.3	36.5	38.0	40.2	39.8	.19	1.5	20.2	18.0
Teeter trend, aver- age of 6 analyses	15.8	19.0	20.5	23.0	24.6	25.3	27.3	29.6	33.0	33.5	36.3	37.2	39.3	40.5	.19	1.3	20.3	19.3
Sallyards trend, aver- age of 16 analyses	16.0	18.7	20.4	23.0	24.5	26.2	27.6	29.4	33.1	34.2	36.7	40.0	40.2	39.7	.20	1.7	20.8	18.4
Haverhill trend, Frog Hollow and Kahn pools, average of 16 analyses	16.6	18.8	20.4	22.4	24.0	26.0	27.2	28.9	33.0	33.2	36.4	37.7	39.4	39.8	.20	1.5	20.4	19.1
Rainbow Bend pool, average of 3 anal- yses	16.0	19.0	20.7	23.0	24.0	25.7	27.0	29.0	32.7	33.3	36.3	37.7	40.7	40.9	.18	1.2	18.3	19.0
Burbank and South Burbank pools, aver- age of 18 analyses	16.2	19.2	20.7	22.5	24.0	25.6	27.2	28.2	32.0	32.7	35.4	36.2	38.0	38.4	.18	1.2	24.4	21.2
Naval Reserve pool, 1 analysis	17.0	20.0	21.0	23.0	24.0	25.0	27.0	28.0	33.0	33.0	35.0	37.0	37.0	38.2	.20	1.4	25.5	21.3

TABLE II
RANDOM ANALYSES SHOWING PERCENTAGE OF DISTILLATE IN FRACTIONS FROM ANALYSES OF BURBANK-SAND CRUDE OILS

Fraction number	Distillation at Atmospheric Pressure										Vacuum Distillation at 40 Millimeters				
	3	4	5	6	7	8	9	10	11	12	13	14	15		
Distillation temperature, °C.	75°-100°	100°-125°	125°-150°	150°-175°	175°-200°	200°-225°	225°-250°	250°-275°	Up to 200°	200°-225°	225°-250°	250°-275°	275°-300°		
Lamont trend	5.0	6.6	6.6	6.0	5.2	5.6	5.6	6.2	5.4	5.8	5.4	4.7	6.3		
Quincy trend	4.6	7.2	5.9	6.1	5.6	5.8	5.5	6.5	5.0	5.0	4.9	5.1	6.0		
Teeter trend	4.8	6.9	6.5	6.7	5.2	5.2	5.5	6.5	3.4	6.1	5.3	4.8	5.0		
Sallyards trend	4.6	6.7	6.2	5.9	5.7	5.2	5.2	6.2	3.7	5.9	5.4	5.3	5.8		
Haverhill trend, Frog Hollow and															
Rahn pools	4.0	7.0	7.3	6.8	5.8	5.9	6.2	7.2	4.3	5.9	5.2	6.2	5.6		
Rainbow Bend pool	6.1	7.3	6.6	6.4	5.4	5.7	5.5	6.7	3.7	5.9	5.6	4.4	5.4		
Burbank and South Burbank pools	4.3	5.8	5.3	5.6	4.9	5.1	5.5	6.3	4.0	5.9	5.8	5.4	5.9		
Naval Reserve pool	3.8	5.3	5.5	5.8	5.0	5.2	5.2	6.5	3.6	5.8	5.6	5.4	6.0		

istics of fractions of the crude oil distilling off at definite temperature intervals. The characteristics of these fractions depend in turn on the relative quantities of the various hydrocarbons present. These hydrocarbons belong to three main groups or types—paraffines, naphthenes, and aromatics. The index number increases in the same order; thus, low indexes (10 or less) indicate paraffines, indexes of 10-40 indicate mixtures of paraffines and naphthenes

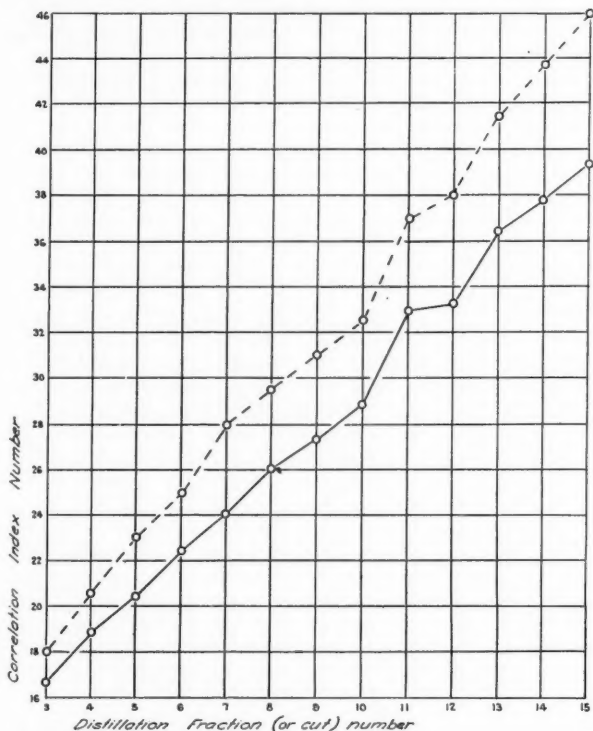


FIG. 2.—Curves showing correlation index numbers of crude oil from Burbank sand (lower curve, representing average of 16 analyses) in several fields in Haverhill trend, and of crude oil from Rock sand (upper curve, representing average of 2 analyses) in Rock field.

(in some, small amounts of aromatics are present), and indexes above 40 indicate increasing amounts of aromatic compounds generally mixed with naphthenes.

In this investigation the crude oils were compared by means of correlation indexes for fractions 3 to 15, the A. P. I. gravity of the crude, the percentage of sulphur, the carbon residue of the crude, the percentage of the residuum, and the A. P. I. gravity of the residuum. Table I gives these data

for 78 samples of crude oil grouped by localities. The localities are shown in Figure 1. The series of index numbers of the 78 analyses from Kansas and Oklahoma are remarkably uniform. The slight variations that occur, with the exception to be noted, are probably within the limits of experimental error of the analyses. The uniformity of the index numbers indicates that the crude oil from these 37 pools is similar in composition.

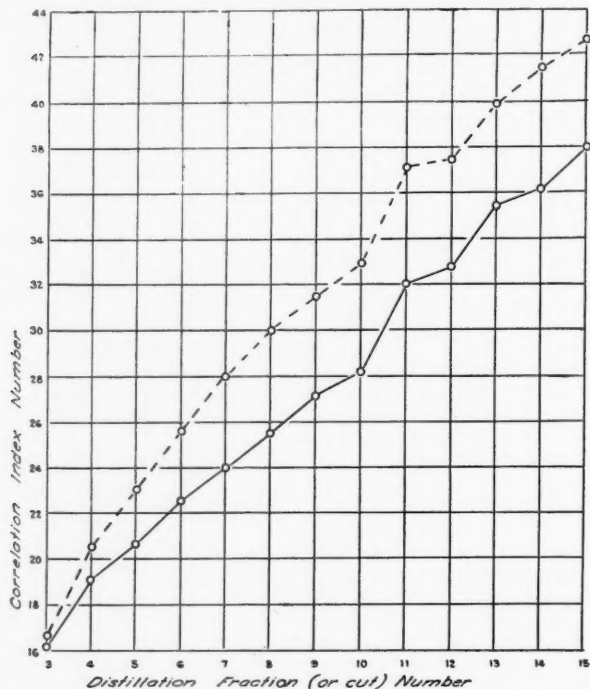


FIG. 3.—Curves showing correlation index numbers of crude oil from Burbank sand (lower curve, representing average of 18 analyses) of the Burbank and South Burbank fields, and of crude oil from Bartlesville sand (upper curve, representing average of 31 analyses) in many fields in southeastern Osage Country.

Further evidence of the similarity of these crude oils is the agreement between the percentage of distillate obtained for each fraction from the different oils. Table II gives these data from analyses selected at random for each locality. The great similarity in the percentages is readily apparent. If averages rather than individual analyses were shown, the agreement would be still closer.

The only deviation from the uniformity shown by the correlation indexes and percentages for the various crude oils is found in those from the Burbank

sand in Oklahoma which have a slightly greater quantity of residuum with a slightly higher A. P. I. gravity than the Kansas oils. This difference in the residuum is also indicated by the slightly lower index numbers for fractions 13, 14, and 15 of these oils than for the corresponding fractions of the Kansas oils. Possibly the demand for Burbank (Oklahoma) oils as a source of lubricating stock is due to the slightly higher paraffine content in the heavier portions of the crude oil. The slightly lower A. P. I. gravity of these Oklahoma crude oils is thought to be due largely to loss of light hydrocarbons in production in a long period of years.

The investigation has shown also that in most places the crude oils from different sands differ in composition. Thus, in Figure 2, an average of the analyses of two samples of crude oil from the Rock sand of the Rock pool in T. 30 S., R. 4 E., Cowley County, Kansas, is compared graphically by the correlation-index method with an average of 16 samples of crude oil from the Burbank sand in the Haverhill trend, which passes southward through Cowley County about 7 miles east of the Rock pool. The crude oil of the Rock pool is more naphthenic throughout all fractions than the crude oil from the Haverhill trend. The oil-bearing sand in the Rock pool is a sand lens in the Cherokee shale not more than 50 feet stratigraphically higher than the Burbank sand of the Haverhill trend.

In Osage County, Oklahoma, the Bartlesville sand lies in the Cherokee shale about 100 feet stratigraphically lower than the Burbank sand. Figure 3 compares graphically an average of the correlation indexes of 31 analyses of crude oils from the Bartlesville sand with an average of the correlation indexes of 18 analyses of crude oils from the Burbank sand of the Burbank and South Burbank fields. The curves indicate that the crude oil from the Bartlesville sand is somewhat more naphthenic than the crude oil from the Burbank sand.

BURBANK SAND

The Burbank sand occurs in the Cherokee shale as disconnected flat-bottomed, convex-topped sand lenses that range in thickness from 50 to a little more than 100 feet, are several times longer than they are wide, and are arranged approximately end to end in systems or so-called trends. Most of the sand lenses range from $\frac{1}{2}$ to $1\frac{1}{2}$ miles wide and from 1 to 7 miles long, but the lens of the Burbank field is about 4 miles wide and 11 miles long. In Kansas the sand lenses occur in two trends or systems whose courses are approximately parallel and about 10 miles apart. The sand bodies lie at depths ranging from about 1,400 feet in western Woodson County, Kansas, to about 3,000 feet in the Burbank field in eastern Kay County, Oklahoma. The oil-bearing sand and other beds have been folded into low anticlines and domes and shallow synclines and basins. In post-Permian time, subsequent to the formation of the folds, the strata of the entire region were tilted westward to form the Prairie Plains homocline. The average regional westward dip of the beds containing the sand lenses is about 30 to 40 feet per mile.

The Burbank sand lenses were formed as offshore bars of the Pennsylvanian sea.⁹ The two systems of offshore bars whose courses are approxi-

⁹ N. W. Bass, Constance Leatherock, W. R. Dillard, and L. E. Kennedy, "Origin and Distribution of Bartlesville and Burbank Shoestring Sands in Parts of Oklahoma and Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 21, No. 1 (January, 1937), pp. 30-66.

mately parallel and about 10 miles apart apparently represent two stages of the sea, which were separated by a relatively short time.

It is believed that after deposition of the offshore bars, the long, narrow salt-water marshes and lagoons landward from the bars were filled with sediment which gradually encroached upon the sand bars until the marsh sediments, heavily laden with partly decayed vegetable and animal remains, completely buried the bars. Doubtless fresh-water marshes were present on the low coastal plain not far back from the salt-water marshes. These marshes also must have followed the migration of the shoreline seaward. The presence in places of coal beds a few feet above the Burbank sand indicates that the fresh-water marshes actually migrated to a position directly above the site of the former shoreline. The presence of beds of limestone containing marine fossils above the coal shows that after a brief period the sea returned landward.

POSSIBLE INTERPRETATIONS

The similarity in composition of the crude oils from the many pools in the Burbank sand suggests that the oil was derived from sediments whose occurrence is restricted to a relatively narrow belt that extends along the system of sand bodies northwestward from Woodson County to northwestern Greenwood County, Kansas, thence southward to southern Osage County, Oklahoma, and undoubtedly farther south—a total distance of 150 miles or more. While the sand bodies were forming the environment apparently was essentially the same along this narrow belt. The most likely source material to supply the oil probably was the rich organic marsh sediments that accumulated as the sand bodies were being formed and interfingered with the sand as great storms occasionally swept sand over the bar into the margin of the marshes.

The total thickness of the source sediments probably does not exceed the thickness of the sand lenses; certainly where coal is present a few feet above the sand the source beds do not extend as high in the sequence of rocks as the coal beds. Probably the strongest evidence that the source beds have a limited vertical extent is the fact that the Rock sand and the Bartlesville sand contain crude oil that is unlike the oil in the Burbank sand, although both of these sands lie within the Cherokee shale, and are separated by small stratigraphic intervals from the Burbank sand. All three sands are oil-bearing in the same region and, therefore, have been subjected to essentially the same treatment as to depth of burial, and regional structural movements.

Few data are available to indicate the time of formation of the oil. The striking similarity of the oil throughout a belt of such length might suggest that the oil formed while the entire region was being uniformly loaded with younger Pennsylvanian sediments soon after the deposition of the sand and marsh sediments.

EFFECT OF STRUCTURAL MOVEMENT

The structural movements that formed the local anticlines, domes, synclines, and basins apparently did not have the slightest effect upon the composition of the crude oil in the Burbank sand, as the analyses of samples from several types of local structural features show the oil to be similar. The tilting movement that formed the Prairie Plains homocline and the recent period of erosion that removed much more overburden in some places than

in others likewise have not affected the oil, as the oil pools in Woodson County, Kansas, lie at an altitude of about 350-400 feet below sea-level and a depth of 1,400 feet, and those in southeastern Butler County lie at an altitude of about 1,300 feet below sea-level and a depth of 2,700 feet, and yet the oils from these two localities are similar.

CORRECTION

UPPER PALEOZOIC OF WESTERN AUSTRALIA: CORRELATION AND PALEOGEOGRAPHY

In the article, "Upper Paleozoic of Western Australia: Correlation and Paleogeography," by Curt Teichert, in the March *Bulletin*, Vol. 25, No. 3, the following corrections should be made.

Page 382, line 20. Read "Carbonaceous" instead of "Bituminous."

Page 385, Figs. 3 and 4. The explanations should be interchanged.

Page 390, Fig. 5. The Wooramel sandstone has been erroneously omitted from the Gascoyne and Minilya columns. See stratigraphic description of Wooramel on page 379.

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library and available, for loan, to members and associates.

THE TERTIARY FORAMINIFERA OF PORTO RICO, BY J. J. GALLOWAY AND CAROLINE E. HEMINWAY

REVIEW BY ALVA C. ELLISOR¹

Houston, Texas

"The Tertiary Foraminifera of Porto Rico," by J. J. Galloway and Caroline E. Heminway. Vol. 3, Pt. 4 of *Scientific Survey of Porto Rico and the Virgin Islands*. 491 pp., 1 fig., 36 pls. The New York Academy of Sciences, Central Park West at Seventy-Ninth Street, New York (April 21, 1941). Price, \$2.00.

This book is an excellent one. It is a concise, meaty, and well presented report of an extensive and detailed study of the Foraminifera of the Miocene and Oligocene formations of Porto Rico.

In the introduction it is stated that "on the island of Porto Rico, rocks of Tertiary age out-crop in two east-west belts on the north and south sides of the large area of Cretaceous igneous and metamorphic rocks which compose the greater part of interior Porto Rico." In the northern area are five formations. In order of descending age, these formations are the Quebradillas (lower Miocene), the Los Puertos (lower Miocene), the Cibao (upper Oligocene), the Lares (upper Oligocene), and San Sebastian (middle Oligocene).

In the southern area are the Juana Diaz formation which probably corresponds in age with the San Sebastian of the north shore, and the Ponce, which is probably the equivalent of several of the north-shore formations.

The total foraminiferal fauna consists of 25 families, 99 genera with 275 species and varieties—88 of which are new. There is a "closer relationship between the various north shore formations than between any one of these formations and the south shore formations."

A check list is given, showing the occurrence and age of the various species in the formations of both north and south shores.

In table No. 3, is shown the relationship of each formation with all the others. "It shows the number of species the two formations have in common and the ratio of this number to the number of species in the smaller of the two formations involved."

The faunas were compared with those of other areas in the Gulf Coast and West Indian region and it was found that they can not be closely correlated with any faunas as yet published. "In no case, except for the Ponce formation, was a percentage of more than 14% discovered. . . . The Porto Rican faunas seem to be in part provincial, in part pelagic, but in most part cosmopolitan and long ranging," and apparently of shallow-water accumulation.

A check list is given, showing abundance and stratigraphic distribution of the Porto Rican foraminiferal faunas. The authors state that at the initia-

¹ Research paleontologist, Humble Oil and Refining Company. Manuscript received, June 24, 1941.

tion of the study it was hoped that new light could be thrown on the exact age of the Porto Rican Tertiary formations. From each formation all the species and their stratigraphic ranges were tabulated. It was found that the age of all the Porto Rican formations is seen to be in the Oligocene or Miocene, evidently not lower than lower Oligocene, or higher than middle Miocene.

All the species are systematically described. The new forms are listed on page 445 and the page on which the description is to be found is printed opposite the name of the fossil. This is an excellent bit of detail that is most helpful to the reader. A complete list of fossil localities is to be found on pages 446-447.

There are 36 plates of fine drawings by the senior author.

An index completes the text.

The specimens are catalogued and deposited in the Paleontological Laboratory, Indiana University.

OBSERVATIONS ON THE EVOLUTION OF THE PACIFIC
OCEAN, BY ALEX. L. DU TOIT

REVIEW BY VICTOR OPPENHEIM¹

Bogota, Colombia

"Observations on the Evolution of the Pacific Ocean," by Alex. L. du Toit.
Proc. 6th Pacific Sci. Congress (1939), pp. 175-83; 1 fig.

This interesting contribution by du Toit outlines the evidence supporting the theory of continental drift as applied to the Pacific. In Mesozoic time the Pacific Ocean was considerably wider; it shrank later, because of encroaching centripetal movements of the surrounding continental massives. Consequently, the history of the evolution of the Pacific is closely related with the neighboring oceans.

The fact that the Pacific, although twice the size of the Atlantic, receives only one-fourth as much drainage as the Atlantic, is explained by the upthrow of the marginal mountain chains, with consequent reversal of the drainages that were originally directed into the Pacific. Oceanic sedimentation thus must have been considerably reduced in the Pacific Basin, at least since Cretaceous time.

The tectonic origin of the deeper parts of the Pacific is suggested by the distribution of the deeps not in the central zones of the basin, but rather, in the marginal sectors, near continental blocks. The encircling land masses are formed of old basements overlain by younger strata with granodioritic plutonics and andesitic effusives. Suggestive of a tectonic belt of weakness are, of course, the chains of active and extinct volcanoes paralleling its shores.

The dominant rocks within the Pacific Basin are basic basalts (oceanites) with subordinate rhyolites. West of South America the shallower section is characterized by nepheline-free lavas, in contrast to the nepheline-bearing types in other parts of the ocean. The circum-Pacific effusives are mainly andesites and dacites.

The ocean floor is assumed to consist of a relatively thin zone of sial of subacid to subbasic composition, underlain by sima. The siallic material can be viewed as the product of magmatic segregation from the subjacent sima,

¹ Consulting geologist, Apartado 381. Manuscript received, June 19, 1941.

without assuming that it represents downsunken continental blocks in the central part of the ocean, as generally believed. The idea of predominantly basic to subbasic oceanic floor finds support in geophysical observations, gravity anomalies, earthquake waves, and volcanicity.

Confirmation of some of du Toit's ideas of drift and crumbling of the advancing continental edge may, in the reviewer's opinion, be found partly in northwestern South America.

Thus, the Amotape Mountains in northwestern Peru, striking northwest away from the main Andean chains, break off on the Pacific coast, assumably having continued as an "advance fold" through what is now the group of Galapagos Islands. The northern extension of the Amotape range probably has been submerged in the process of general breaking up, faulting, and intense magmatic activity along the northwestern part of the Continent that took place in early Mesozoic at the close of Jurassic time.

In the reviewer's opinion it is indeed probable that the early Jurassic seas extended not only through the largest western part of the Continent,² but also connected in many places with the present Pacific, forming an extended ocean, as suggested by du Toit.

As further evidence of an assumably westward-directed motion of the northwestern part of the Continent, the reviewer could cite the numerous regional thrust faults observable in many ranges of the Andes. From the point of view of western drift, the separation, according to the reviewer, of the Sierra Nevada de Santa Marta massif from the old metamorphic blocks of the Goajira Peninsula, which apparently took place in pre-Cretaceous time, could also be regarded as confirmations of the same drift.

The causes of the drift, according to du Toit, can be attributed, among other factors, to the "assimilation of fold roots belonging to the encroaching orogenic fronts by magma generated within what can be termed the 'basaltoid layer'." The main factor in drift is thus caused by "deep seated melting beneath the more mobile leading edge of a block." The subcrustal melting beneath the sial cap could be attributed to radioactive energies. Due to this process, on a large scale, can be explained the recurrence of andesites and granodiorites in the circum-Pacific compression girdle, while the intra-Pacific region, remaining neutral and submitting to slight lateral tension, is characterized by young basalts emitted mainly from volcanic vents.

The paper is thought-provoking and many of its arguments seem to be applicable to the Pacific coast of South America.

² Victor Oppenheim, "Jurassic-Cretaceous (Giron) Beds in Colombia and Venezuela," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22, No. 9 (September, 1940).

THE DIVISIONS OF THE UPPER CRETACEOUS AND
TERTIARY IN NEW ZEALAND, BY H. J. FINLAY
AND J. MARWICK

THE TERTIARY GEOLOGY OF AUSTRALIA, BY
F. A. SINGLETON

REVIEW BY BURTON WALLACE COLLINS¹
Gisborne, New Zealand

"The Divisions of the Upper Cretaceous and Tertiary in New Zealand," by H. J. Finlay and J. Marwick. *Trans. Roy. Soc. New Zealand*, Vol. 70, Pt. 1 (June, 1940), pp. 77-135.

"The Tertiary Geology of Australia," by F. A. Singleton. *Proc. Roy. Soc. Victoria*, Vol. 53, Pt. 1 (February, 1941), pp. 1-125.

H. G. Schenck has recently reviewed in this *Bulletin*² a paper on "The Divisions of the Tertiary of New Zealand" by H. J. Finlay and J. Marwick.³ The same authors have more recently published a much longer paper containing fuller lists of species (especially as regards Foraminifera) and also including the Upper Cretaceous formations (Albian-Danian). Sections on "Outside Macrofaunal Correlations" and "Outside Correlations by Foraminifera" are valuable contributions toward placing the New Zealand stages in their correct position in the international time-scale. Most of the significant points of paleontological comparison between New Zealand and other countries (especially Australia, Europe, South America, Mexico, Texas, California, and the Netherlands East Indies) are mentioned and discussed in detail.

The same system of describing the stages as commended by Schenck is followed, but more detail is given. Schenck remarks that it is his opinion that the authors should have selected as type localities of the stages those places where the subjacent and superjacent stages are present in the same section and in similar facies. This would have been impossible for two reasons: (1) the authors were bound by the law of priority; (2) the New Zealand Tertiary sequence is nowhere complete or even nearly so; in many localities only one or two stages are present, and the rocks are isolated from other Tertiary strata.

The system of subdivision of the Tertiary (and Upper Cretaceous) of New Zealand with the use of local stage-names, was first proposed by J. Allan Thomson in 1916.⁴ Since then new stages have been proposed by various authors with various type localities, as geological work in New Zealand was extended and strata found which could not be correlated paleontologically with the then accepted stages. The latest revision of the New Zealand Tertiary divisions, prior to that of Finlay and Marwick here reviewed, was by R. S. Allan in 1933.⁵ This author was the first to cite lists of characteristic

¹ New Zealand Petroleum Company. Manuscript received, June 21, 1941.

² *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25 (1941), pp. 763-66.

³ *Proc. Sixth Pacific Sci. Cong.*, Vol. 2 (1940), pp. 505-21.

⁴ J. A. Thomson, "On Stage Names Applicable to the Divisions of the Tertiary in New Zealand," *Trans. New Zealand Inst.*, Vol. 48 (1916), pp. 28-40.

⁵ R. S. Allan, "On the System and Stage Names Applied to Subdivisions of the Tertiary Strata in New Zealand," *Trans. New Zealand Inst.*, Vol. 63, Pt. 2 (February, 1933), pp. 81-108.

species (mostly molluscs and brachiopods) and redefined all the stages, using a uniform system, an example of which is as follows.

The Castlecliffian may be defined as the interval of time represented by the deposition of the Wanganui, Kai-iwi, and Okehu beds of Park (1887), and as well such periods as may be represented therein by non-deposition or erosion.

Since this paper, Allan has (1938) proposed the Duntroonian stage, and Finlay (1939) the Kaiatan and Whaingaroan as subdivisions of the large Ototaran stage, and the new Opoitian stage. No new stages are proposed by Finlay and Marwick in their recent papers. They merely list the ranges of fossils with respect to the stages already in use.

The important paper on "The Tertiary Geology of Australia" brings the subdivision of the Australian Tertiary into line with that of New Zealand by re-defining stages in the same manner as Allan (without acknowledgment) and defining several new ones. As an example may be given the following.

The Janjukian may be defined as the interval of time represented by the deposition of the marine beds outcropping in the coastal sections, about three miles in length, between Rocky Point and the mouth of Spring Creek, in the Parish of Jan Juc, and proved in borings to a depth of 170 feet below sea level, as well as those represented therein by non-deposition or erosion.

Singleton in this paper proposes a tentative correlation of the Australian and New Zealand stages as given in Table I. Discussing the value of a local stratigraphic time-scale for Australia he states (p. 62):

TABLE I
TENTATIVE CORRELATION OF NEW ZEALAND AND AUSTRALIAN TERTIARY STAGES

<i>Europe</i>		<i>New Zealand</i>	<i>Australia</i>
PLIOCENE	Upper	Castlecliffian	Werrikooian (New stage?)
	Middle	Nukumaruan	Adelaidean
	Lower	Waitotaran Opoitian	Kalimnan
MIOCENE	Upper	Urenuian Tongaporutuan	Cheltenhamian
	Middle	Awamoan	Balcombian
	Lower	Hutchinsonian	Batesfordian Janjukian
OLIGOCENE	Upper	Waitakian Duntroonian	(New stage?) Anglesean
	Middle	Whaingaroan	(New stages?)
	Lower	Kaiatan	
EOCENE	Upper	Tabuian	Giralian
	Middle	Bortonian	
	Lower		

Since he (the writer) believes that only the broadest correlations are possible with Tertiary deposits in distant parts of the world, and that while even internal correlations are not yet satisfactorily established, it is impracticable to equate local stages with those of Europe, the reference in the correlation table to subdivisions of the major European units is a tentative one. For this reason the use of a local nomenclature for stages is important, as has been proved in the parallel case of New Zealand, and its partial discontinuance by some Australian authors is to be deplored as a retrogressive step, tending towards that confusion which local names were designed to reduce.

Should it be proved, as is probable, that stages exist which are not covered by the names already proposed, further stage names should be introduced, provided they are rigorously defined.

Besides discussing Australian marine Tertiary stratigraphy, Singleton gives accounts of the non-marine deposits and igneous rocks of the era, and also gives a very interesting summary of Tertiary diastrophism and paleogeography. Altogether the paper is the most comprehensive review of the Tertiary era in Australia yet published. An account of the New Zealand Tertiary to supplement Finlay and Marwick's paleontological data is now urgently required. The best summary recently published is by Henderson,⁶ but this is confined more or less to possible oil-bearing regions.

The correlation and stratigraphy of the New Zealand Tertiary deposits are at the present time of great interest on account of the large amount of work now being done in oil exploration.

Finally, American micropaleontologists may be interested in the following foraminiferal comparisons culled from the two papers here reviewed and others by Crespin⁷ and Parr,^{8,9} on Australian Foraminifera.

CRETACEOUS (New Zealand). No trace yet of *Pseudotextularia*, *Ventilabrella*, *Eouwigerina*, *Pseudouwigerina*, *Bolivinita* (*elyi* Cushman), and only very rare specimens of *Globotruncana*, and *Gumbelina*. *Globigerina cretacea* d'Orbigny is found only in the Clarentian stage (considered to be Albian-Coniacian in age); in America it is still common in the Texas Navarro, but in New Zealand is replaced in beds of approximately the same age by a form close to the Navarro *rugosa* Plummer. The Piripauan stage (Santonian-Campanian) contains species of *Palmula* very close to *reticulata* (Reuss), *semireticula* (Cushman and Jarvis), and *primitiva* Cushman, a *Fronicularia* like *dimidia* Bagge, and a *Planularia* close to *simondsi* (Carsey)—all prominent Navarro species. The restricted Cretaceous genus *Bolivinitoides* (as *dorreeni* Finlay, of the *delicatula* Cushman group) also occurs at this horizon, while above it in the section occurs *Nuttallides alatus* (Marsson), also known from high in the Cretaceous of Germany, Arkansas, and Trinidad. *Gyroidina globosa* v. Hag., conspicuous in the Navarro, is equally so in the Piripauan, but absent above and below. *Rotamorphina cushmani* Finlay is known only from the upper Piripauan and the same upper Navarro Trinidad horizon. Of particular interest is the genus *Rzehakina* Cushman, which is abundant in and limited to the Piripauan stage. The known occurrences of *R. epigona* (Rzehak) in the middle and upper Velasco of Mexico, the upper Navarro of Trinidad, the Maestrichtian and Danian of French

⁶ J. Henderson, "Petroleum in New Zealand," *New Zealand Jour. Science and Technology*, Vol. 19, No. 7 (December, 1937), pp. 401-26.

⁷ I. Crespin, "Tertiary Rocks in North-West Australia," *Rept. Australia and New Zealand Assoc. Adv. Sci.* (23d Meeting, Auckland, 1937), p. 443.

⁸ W. J. Parr, "Upper Eocene Foraminifera from Deep Borings in King's Park, Perth, Western Australia," *Jour. Roy. Soc. Western Australia*, Vol. 24 (July, 1938), pp. 69-101.

⁹ W. J. Parr, "Foraminifera of the Pliocene of South-Eastern Australia," *Mines Dept. Victoria Min. Geol. Jour.*, Vol. 1, No. 4 (January, 1939), pp. 65-71.

- North Morocco, and the "Alttertiar" of Austria (shown by Glaessner to be really late Cretaceous) suggest that the age of the New Zealand beds must be close to the Tertiary boundary—certainly no older than Santonian and no younger than Danian.
- EOCENE** (New Zealand). No lower Eocene recognized. Sharp change in lowest Bortonian from Cretaceous. No Cretaceous lingerers as in the Texas Midway. A form deceptively like *Eowigerina* occurs, but is more advanced in development and has been separated as *Zeauwigerina* Finlay. *Assilina*, *Discocyclina* and *Asterocyclina* occur, but *Camerina* is absent. *Hantkenina* (as *australis* Finlay) has a range upper Bortonian-Kaiatan. This is the same range (middle Eocene-lower Oligocene) as the genotype in America. Affinities with the Eocene of Mexico (especially the Aragon formation) are: *Nuttalides* Finlay of the *trumpyi* type; *Globorotalia crater* Finlay (close to *crassata* Cushman and *aragonensis* Nuttall); the Bortonian genus *Aragonia* Finlay (of *Bolivinoidea* affinity) has close Mexican allies in the Velasco and Aragon; *Marginulinopsis waitparaensis* Finlay is extremely close to *M. asperuliformis* Nuttall, an index species of the Aragon, while *M. marshalli* Finlay is just as close to the Californian *nudicostata* (C. and H.).
- EOCENE** (Australia). *Fronicularia mucronata* Reuss (typically Upper Cretaceous but lower Eocene of Texas); *Bolivinoidea eocenica* (Cushman and Barksdale), *Dentalina colei* Cushman and Dusenbury, and *Gyroidina soldanii* var. *octocamerata* Cushman and Hanna are also American Eocene species; *Discorbis assulatus* Cushman (upper Eocene of United States); *Globigerina orbiformis* Cole (mexicana Cushman) (upper and middle Eocene of Mexico). *Vaginulina subplumoides* Parr is near *plumoides* Plummer (lower Eocene of Texas); *Gumbelina venezuelana* var. *rugosa* Parr is near *venezuelana* Nuttall (upper Eocene of Venezuela); *Pulvinulinella obtusa* (Burrows and Holland) var. *westraliensis* Parr appears to be present in the Eocene of the United States. *Valulineria sculpturala* Cushman and *Angulogerina subangularis* Parr (close to *vicksburgensis* Cushman) show affinities with the lower Oligocene. Among the larger forms are *Camerina*, *Discocyclina*, *Asterocyclina*, and *Pellatispira*.
- OLIGOCENE** (New Zealand). Most striking genus is *Rotaliatina* Cushman which has a range in New Zealand of upper Bortonian-Whaingaroan, compared with middle and upper Eocene in Mexico. Abundance of several species of *Asterigerina*, replaced by *Amphistegina* in Whaingaroan and later stages. From the basal Oligocene (Kaiatan) have been described *Robertina lornensis* Finlay (close to *ovigera* Terquem and the German lower Oligocene *germanica* Cushman and Parker), and *Ceratobulimina lornensis* Finlay (close to American Eocene *perplexa* Plummer).
- OLIGOCENE** (Australia). Three species of *Lepidocyclina* (*Eulepidina*) occur in rocks assigned to the upper Oligocene to lower Miocene.
- MIOCENE** (New Zealand). *Miogypsina* is confined to the Hutchinsonian; also various species of *Lepidocyclina* (all nephrolepidine). *Amphistegina lessonii* d'Orbigny is first abundant in the Hutchinsonian. *Miogypsinoides* is confined to the lower Hutchinsonian in New Zealand and to the top of stage "e" and base of "f" in the Netherlands East Indies (Aquitanian-Burdigalian). Little relationship with American Miocene.
- MIOCENE** (Australia). Several species of *Lepidocyclina* (*Eulepidina*) and (*Nephrolepidina*), and *Cyclocypeus* occur in the Batesfordian (?) limestones of North West Cape Range. Other Batesfordian foraminifera include: *Operculina*, *Amphistegina lessonii* d'Orbigny, and *Gypsina howchini* Chapman. In the Balcombian occur: *Nephrolepidina*, *Amphistegina lessonii* d'Orbigny, *Flosculinella bontangensis*, and *Trillina howchini* Schlumberger. The last-named is known elsewhere only from the Miocene of Java (stage "e"), Borneo ("e" and "f"), Philippines, Pembla Island near Zanzibar, Irak, and the Island of Paxos in Greece.
- PLIOCENE** (New Zealand). *Uvigerina pigmea* d'Orbigny and *Bulmina echinata* d'Orbigny, as well as a modern globigerinid assemblage.

- PLIOCENE (Australia). *Elphidium advenum* (Cushman), *Buliminella elegantissima* (d'Orbigny), *Rectobolivina striatula* (Cushman), *Uvigerina cf. pigmea* d'Orbigny, *Bulimina echinata* d'Orbigny, *Flintina triquetra* (Brady), *F. intermedia* (Howchin).

RECENT PUBLICATIONS

CALIFORNIA

*"Structural Features of the Virgin Spring Area, Death Valley, California," by Levi F. Noble. *Bull. Geol. Soc. America*, Vol. 52, No. 7 (New York, July 1, 1941), pp. 941-1000; 20 pls., 6 figs.

*"Deformation in the Interval Mt. Lyell-Mt. Whitney, California," by Evans B. Mayo. *Ibid.*, pp. 1001-84; 13 pls., 26 figs.

*"Submarine Topography Off the California Coast: Canyons and Tectonic Interpretation," by Francis P. Shepard and K. O. Emery. *Geol. Soc. America Spec. Paper 31* (New York, May 28, 1941). 171 pp.; 18 pls., 42 figs., 4 charts in pocket.

"Geology of the Kettleman Hills Oil Field, California, Stratigraphy, Paleontology, and Structure," by W. P. Woodring, Ralph Stewart, and R. W. Richards. *U. S. Geol. Survey Prof. Paper 195* (1941). 170 pp.; 57 pls., 15 figs. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, \$1.50.

ECUADOR

*"The Geology and Paleontology of the Cuenca-Azogues-Bibian Region Provinces of Canar and Azuay, Ecuador," by R. A. Liddle and K. V. W. Palmer. *Bull. Amer. Paleontology*, Vol. 26, No. 100 (July 7, 1941), pp. 361-421; 11 pls. (geologic map, stratigraphic structural sections, photographs of rock exposures and fossils). Paleontological Research Institution, Ithaca, New York. Paper. Octavo. Price, \$1.50.

GENERAL

*"Pamlico Fossil Echinoids," by Willard Berry. *Proc. U. S. Natl. Mus.*, Vol. 90, No. 3113 (Washington, D. C., 1941), pp. 443-45; Pls. 63-65.

*"Scope and Content of the Petroleum Engineering Curriculum," by Lester C. Uren. *Amer. Inst. Min. Met. Eng. Tech. Pub. 1350. Petroleum Technology* (New York, July, 1941). 8 pp.

*"The Effect of Crooked Wells on Exploitation," by H. C. H. Thomas. *Jour. Inst. Petroleum*, Vol. 27, No. 211 (Birmingham, England, May, 1941), pp. 157-64; 2 figs.

**Bibliography and Index of Geology Exclusive of North America, Volume 8—1940*, by John M. Nickles, Marie Siegrist, and Eleanor Tatge. *Geol. Soc. America*, New York (1941). 386 pp.

**Geology, 1888-1938*. Fiftieth Anniversary volume of the Geological Society of America (New York, June, 1941). 578 pp. 21 chapters, by as many authors, each devoted to a field of generally recognized prominent specialistic interest in the science of geology. The preface by Charles P. Berkey includes "an analysis of the structure of organized geology of the present day, showing its fields of interest, indicating its major branches, and the form and relation of the numerous specialistic societies now recognized in Geologic Science."

**Annotated Bibliography of Economic Geology for 1940*, Vol. 13, No. 1 (April, 1941). 165 pp. "Petroleum and Natural Gas," pp. 605-794. Prepared

under the auspices of the Society of Economic Geologists, Urbana, Illinois. Annual subscription, \$5.00.

Done in Oil, by David D. Leven. 1084 pp.; 26 photographs, 22 maps, 29 graphic illus., 7 charts, 108 tables, 5 pp. of bibliography, glossary, 5 appendices. The Ranger Press, Inc., 347 Fifth Avenue, New York. Price, \$10.

ILLINOIS

"Structure of Herrin (No. 6) Coal Bed in Madison County and Western Bond, Western Clinton, Southern Macoupin, Southwestern Montgomery, Northern St. Clair, and Northwestern Washington Counties," by J. Norman Payne; with "Notes on the Oil and Gas Possibilities," by A. H. Bell. *Illinois Geol. Survey Cir.* 71 (Urbana, August 11, 1941). *Gratis*.

IRAQ

*"Die Erdölfelder des nördlichen Irak" (The Oil Fields of Northern Irak), by C. Schmidt. *Oil und Kohle*, Vol. 37, No. 17 (Berlin, May 1, 1941), pp. 287-97; 18 figs. (sketch map, photographs, stratigraphic sections).

KANSAS

*"Ground-Water Conditions in the Vicinity of Lawrence, Kansas," by Stanley W. Lohman. *Kansas Geol. Survey Bull.* 38, 1941 Repts. of Studies, Pt. 2 (Lawrence, June, 1941), pp. 17-64; 2 pls.

*"New Permian Corals from Kansas, Oklahoma, and Texas," by Raymond C. Moore and Russell M. Jeffords. *Ibid.*, Pt. 3, pp. 65-120; 8 pls.

*Upper Pennsylvanian Gastropods from Kansas," by Raymond C. Moore. *Ibid.*, Pt. 4, pp. 121-64; 3 pls.

KOREA

*"On Neurophyllum Koreanicum Gen. et Sp. Nov. from the Lower Permian Beds of Northern Tyosen (Korea)," by Enzo Kon'no. *Mem. Kyusyu Imp. Univ. Geol. Inst. Faculty of Science*, Ser. D (Geology), Vol. 1, No. 2 (Hukuoka, Japan, March, 1941), pp. 23-42; 2 fossil pls.

MEXICO

*"The Front Ranges of Sierra Madre Oriental, Mexico, from Ciudad Victoria to Tamazunchale," by Arnold Heim. *Eclogae Geol. Helvetiae*, Vol. 33, No. 2 (1940), pp. 313-52; 3 folded pls. (geologic map in colors, and structural sections), 10 figs. In English. Published by E. Birkhaeser and Company, Basle, Switzerland.

PENNSYLVANIA

*"Music Mountain Oil Pool and Other Oil Pools in Lafayette Township, McKean County, Pennsylvania," by Chas. R. Fettke. *Pennsylvania Topog. and Geol. Survey Prog. Rept.* 125 (Harrisburg, June, 1941). 34 pp.; 9 figs., 1 table.

*"Early Devonian and Late Silurian Formations of Southeastern Pennsylvania," by Charles K. Swartz and Frank M. Swartz. *Bull. Geol. Soc. America*, Vol. 52, No. 8 (New York, August 1, 1941), pp. 1130-91; 1 pl., 2 figs.

ROCKY MOUNTAIN REGION

*"Cambrian Geography and Sedimentation in the Central Cordilleran Region," by Charles Deiss. *Bull. Geol. Soc. America*, Vol. 52, No. 7 (New York, July 1, 1941), pp. 1085-1116; 10 figs.

TENNESSEE

*"Silurian Lithology in Western Tennessee and Adjacent States," by John R. Ball. *Bull. Geol. Soc. America*, Vol. 52, No. 7 (New York, July 1, 1941), pp. 1117-28; 1 pl., 3 figs.

TEXAS

*"West Texas," compiled by *Oil and Gas Jour.*, Vol. 40, No. 9 (Tulsa, July 10, 1941), 2 pp. between pp. 48 and 49; generalized stratigraphic log sections in colors.

*"Slaughter West Texas Area Fast Approaching Record in Acreage and Activity," by Gilbert M. Wilson. *Oil Weekly*, Vol. 102, No. 9 (Houston, August 4, 1941), pp. 35-51; 4 photographs, 1 graph of production, 1 stratigraphic column, 1 map of West Texas-New Mexico fields, 1 folded insert development and property map.

ASSOCIATION DIVISION OF PALEONTOLOGY AND MINERALOGY

**Journal of Sedimentary Petrology* (Tulsa, Oklahoma), Vol. 11, No. 2 (August, 1941).

"The Frontiers of Sedimentary Mineralogy and Petrology," by W. H. Twenhofel.

"Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles," by W. C. Krumbein.

"A New Device for Sampling Lake Sediments," by Ira T. Wilson.

"Sediments of Pecos River, New Mexico," by Raymond Sidwell.

"Heavy Residues from Some Upper Cretaceous Sediments at Gingin, Western Australia," by Dorothy Carroll.

"Transportation of Rock Particles by Sea-mammals," by K. O. Emery.

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"Local Areal Variation of Heavy Minerals in Beach Sand," by W. C. Rasmussen.

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Memorial

GEORGE MARTIN HALL

(1891-1941)

George Martin Hall died in Baltimore, Maryland, on April 28, 1941, after a period of failing health and illness of more than four years. He was born in Baltimore, September 13, 1891, the son of George Arlow Hall and Alice Josephine (Higgins) Hall.

His early education was in the public schools of Baltimore and he graduated from the Baltimore City College in 1909. In the fall of 1911, he entered The Johns Hopkins University and received the degree of Bachelor of Arts in 1915. He then pursued graduate work in the department of geology until he entered the Signal Corps, United States Army, in March, 1918. He was commissioned as Second Lieutenant in August, 1918, and served until November, 1920. He returned to The Johns Hopkins University and received the degree of Doctor of Philosophy in 1923. He remained at the university as instructor in geology until the fall of 1926.

In 1926 he went to the University of Tennessee as associate professor of geology and in 1929 was appointed professor and head of the department of geology and geography. He was on leave of absence on account of ill health during the academic year 1940-41.

His geologic field career began with the Maryland Geological Survey. In 1915 he worked on the Silurian rocks of western Maryland and in 1916 he investigated the fireclays of Allegany and Garrett counties. The summer of 1917 was spent in Kentucky and Kansas for the Roxana Petroleum Corporation. In June, 1921, he was appointed an assistant geologist on the United States Geological Survey and assigned to the ground-water division of the Water Resources Branch, a connection which he maintained to the time of his death. In the earlier years he devoted his summers to field work. In the later years he spent much of his summers in the office in Washington in scientific and administrative work. He became especially interested in the problem of ebbing and flowing springs.

Professor Hall liked people and was a regular attendant at the meetings of the scientific and technical societies. He was a member of the American Association of Petroleum Geologists, the Geological Society of America, the Mineralogical Society of America, the Society of Economic Geologists, and the American Institute of Mining and Metallurgical Engineers. He had hosts of friends in all of these societies. In the community in which he lived and spent the greater part of his scientific career, he was likewise an active participant in the scientific and civic life. He served as president of the Knoxville Technical Society in 1932 and as president of the Tennessee Academy of Science in 1934. He was a charter member of the Knoxville Science Club and served as its first president in 1934. His interest in civic affairs was manifested by active participation in the Knoxville Rotary Club and by his compliance with repeated requests for public lectures and talks to lay audiences.

Before impaired by failing health, his personality was full of vigor and energy. An alert and inquiring mind and a retentive memory gave him a

broad and accurate knowledge of many subjects and made his conversation instructive and entertaining. A homely honesty and unpretentious personality, coupled with fearlessness in his convictions, made him plain and frank in speech. But his outspokenness was always in such good humor and spirit and with such geniality that he radiated cheer and good will, and the many who knew him welcomed his company.



Knaff & Brakebill, Knoxville, Tennessee

GEORGE MARTIN HALL

Dr. Hall enjoyed life and never took himself too seriously. This trait, together with a degree of corpulence, tended to give the impression that he was an easy-going person who did not take life seriously, but at heart he was a hard and conscientious worker. A close friend of his very aptly said of him: "George was a genial, easy-going man but had much drive particularly in human affairs. As a boy he had worked in the City Hall, Baltimore, and he never forgot the lessons learned in this school of practical politics. He had a certain humorous, ribald cynicism as a result of this experience. It made him a success and supported him in his army career. He was under this exterior a modest and sincere idealist. His devotion to science and teaching was very

real and the result of much thought by a man who had seen the other aspects of the world."

The span of his active scientific career was only 14 years. Though he may not have accomplished big things, he accomplished much. His bibliography constitutes a creditable contribution to the literature of geologic science. Perhaps more important and valuable was his influence on his colleagues and his students at the University of Tennessee in his constant endeavor for progress. His active interest in and untiring efforts in building up the University Museum of Geology leaves that as a fitting tangible memorial of his university career. His devotion to the advancement of his department, to the students who studied with him, and to the furtherance of scientific progress in his adopted community and State built an even greater though less tangible monument.

JOSEPH T. SINGEWALD, JR.

BALTIMORE, MARYLAND
August 18, 1941

BIBLIOGRAPHY OF GEORGE MARTIN HALL

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CHARLES THEODORE CASEBEER

(1905-1941)

Charles Theodore Casebeer died at Olney, Illinois, on the evening of June 6, 1941, as a result of injuries received in an automobile accident on the morning of that same day. His home was 1719 Huntington Drive, Nichols Hills, Oklahoma City, Oklahoma.

He is survived by his widow, Jone Steel Casebeer, whom he married at Oklahoma City, January 24, 1931; his parents, Mr. and Mrs. C. S. Casebeer

*Curtis Studios, Oklahoma City*

CHARLES THEODORE CASEBEER

of Kalispell, Montana; two brothers, Dr. Harvey L. Casebeer and Dr. R. Lawrence Casebeer of Butte, Montana; three sisters, Mrs. Edward Thurber, Miss Virginia Casebeer of Detroit, Michigan, and Mrs. Harry Harrod of Kansas City, Missouri.

Mr. Casebeer was born at York, Nebraska, on June 12, 1905. He entered grade school at Lewistown, Montana, where the Casebeers resided from 1910 to 1914. The family returned to York in 1914 and Charles received the re-

mainder of his grade school and all of his high school education in the public schools of that City. He graduated from York High School in the spring of 1925. After graduation from high school he studied the next year at York College. He then attended Nebraska University both semesters of the years 1926-27, 1927-28, 1928-29, and the 1929 summer session. When he left Nebraska University to take a job he lacked a few hours credit for graduation, which he secured through extension courses in 1932. He was graduated with a Bachelor of Arts degree in geology, January 27, 1933. He belonged to Delta Chi social fraternity and Sigma Gamma Epsilon honorary geological fraternity. While at Nebraska University, Charles worked as an apprentice mortician, which experience very definitely prejudiced him against the conventional method of burial.

In October, 1929, Casebeer was employed by Coline Oil Corporation at Oklahoma City, at a time when that company was in the midst of a drilling campaign in the Oklahoma City field. He served that company until January 31, 1938, as a geologist and petroleum engineer. During those years he engaged in almost every phase of petroleum geology and engineering, doing drafting, detailed and reconnaissance surface mapping, subsurface work of all kinds, surveying, designing for buildings, and similar work. In his engineering work he showed himself to be a true craftsman as he was thorough in every detail. It was as a surface reconnaissance geologist, however, that he was at his best, for he seemed to have a sixth sense when it came to determining the structure of an area as he rapidly got what he called the "feel" of it.

It was his thoroughness in a study of subsurface of the Oklahoma City field which he was starting for the re-working of old wells which caught the attention of representatives of Casebeer's only other oil employer—the Lane-Wells Company. His rise in that organization was rapid. The responsible position which he held at the time of his death showed that he had become an able executive, a feat which far too few geologists and engineers can perform. He was Lane-Wells' sales manager of the Mid-Continent division, which included Illinois and some of the Rocky Mountain states. Many of the sales engineers of that excellent organization were developed under his careful guidance. The sales of products and services of that company within his division increased continuously under his direction.

Because of his open countenance and impressive looks, "Chuck" commanded the attention of people. Because of his earnestness of purpose and fairness in dealing, he made friends of them. Because of his zeal for life and living and his sincere interest in those whom he knew, he kept them as his friends.

The Lane-Wells Company has lost an able executive in Casebeer's untimely passing. The oil industry has lost a young man who was able to take its highly technical problems and translate them into comprehensible terms; to take its new and little understood tools and show the practical man how to use them. His ever increasing circle of friends has lost a member who knew that "the way to have a friend is to be one." His loved ones have lost a devoted husband, a duteous son, and a brother who could always be depended on for a helping hand.

E. A. PASCHAL

AMARILLO, TEXAS
August 11, 1941

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION NATIONAL DEFENSE POSITIONS OPEN FOR INDUSTRIAL SPECIALISTS

Trained personnel in every branch of industry, science and business is being called to Government service in this time of emergency. Individuals who know industrial methods and processes from first-hand experience are needed to contribute their part toward the integration of the expanding defense program. The Civil Service Commission has announced an examination for Industrial Specialist positions paying from \$2,600 to \$5,600 a year. The examination (Announcement No. 102) is open for an indefinite period.

Industrial specialists may be called upon to perform any of three types of jobs. The first is that of liaison representative in developing and maintaining working relationships with manufacturers of materials or equipment vital to the defense program. Secondly, they may act as consultants on industrial materials, methods and processes, or they may examine and evaluate data secured from the reports of various industrial concerns. The third possible assignment is that of investigator and analyst in the field of industrial materials, which involves the collection of data on production techniques, uses, consumption, and market supplies of particular materials.

To qualify for these positions, experience is required that has given the applicant a thorough knowledge of production methods and processes in one or more manufacturing industries. This experience may have been in industrial management, planning, engineering, cost accounting, business analysis, or research. Applicants may substitute resident study in an educational institution above high-school grade, up to a maximum of 4 years, for this general experience. For each of the positions, applicants must have had some experience in one (or in a combination of not more than three) of the following industries:

- Iron and steel
- Non-ferrous metals
- Machine tools
- Ordnance
- Aircraft, marine and automotive equipment
- Railroad repair shops
- Radio and other electrical equipment, supplies and apparatus
- Textiles
- Forest products
- Paper
- Printing and publishing
- Chemicals and allied products
- Plastics
- Petroleum and coal products
- Rubber products
- Stone, clay and glass products
- Leather and its manufactures
- Food and kindred products

Applicants are rated on their education and experience and upon corroborative evidence. An oral examination may be given to determine further an applicant's qualifications for the positions. No written test will be given.

Further information and application forms may be obtained at any first- or second-class post office or from the Civil Service Commission in Washington.

SURGE JOHN TAYLOR has resigned from University Lands at Midland to accept a position on the geological staff of the Seaboard Oil Company in the division office at Midland, Texas.

DONALD L. NORLING, of the Shell Oil Company, Inc., has been transferred from Wichita, Kansas, to Tulsa, Oklahoma, where he is to be assistant district geologist.

Ensign JOHN S. HEROLD, on active duty in the United States Navy, has left the Forest Development Corporation, Midland, Texas. He may be addressed: U.S.S. *Wm. P. Biddle* in care of the Postmaster, New York City.

H. M. KIRK, resident geologist, The Atlantic Refining Company, is now based in Port-au-Prince, Haiti. In August, he was at home on vacation at Bozeman, Montana.

E. H. DAHLGREN, who has been with the oil and gas unit of the Securities and Exchange Commission, is senior petroleum analyst in the Office of Petroleum Coördinator for National Defense, Washington, D. C.

H. WHITMAN PATNODE, recently research associate of the American Petroleum Institute at the United States Geological Survey, Washington, D. C., is in the employ of the Gulf Research and Development Corporation, Pittsburgh, Pennsylvania.

PAUL K. GOODRICH, recently of Houston, Texas, is a captain at the 3d Army Headquarters, Presidio of Monterey, California.

JAMES McNAB has enlisted in the United States Army Air Corps as an aviation cadet in aerial photography. He is at Lowry Field, Denver, Colorado.

JULIAN KINGSBURY PAWLEY is first computer on a seismograph crew with the General Geophysical Company, Gulf Building, Houston, Texas.

M. H. BILLINGS may be addressed in care of the Non-Metal Economics Division, United States Bureau of Mines, Washington, D. C.

J. O. ALLEN has moved from Spaulding, Oklahoma, to Maracaibo, Venezuela. His address is Apartado 172.

CHARLES W. FOWLER, JR., has returned to the United States, after 2 years with the Y.P.F. of Argentina in the Comodoro Rivadavia area as geologo jefe distrito. His address in Azalea, North Carolina.

GERTRUDE M. DRACH, recently with Case, Pomeroy and Company, New York, is a petroleum production analyst in the Office of Petroleum Coördinator for National Defense, Production Division, Interior Building, Washington, D. C.

REGINALD G. RYAN has moved from Houston to 1215 West Russell Place, San Antonio, Texas.

ROGER L. MESSMAN is in the geological department of the Continental Oil Company at Larned, Kansas.

G. J. LOETTERLE, of the Shell Oil Company, Inc., has moved from Tyler to Houston, Texas.

HERBERT V. LEE, recently with the Colombian Petroleum Company at Cucuta, is now with The Texas Company (Venezuela), Ltd., Apartado 267, Caracas, Venezuela, S. A.

HUNTER YARBOROUGH, JR., recently geologist for the Humble Oil and Refining Company at Mobile, Alabama, has entered aviation training at the United States Naval Reserve Aviation Base, Atlanta, Georgia.

JULES BRAUNSTEIN, of the Shell Oil Company, Inc., has been transferred from Houston, Texas, to 805 Slattery Building, Shreveport, Louisiana. His duties as paleontologist have been increased to those of paleontologist and stratigrapher.

RAYMOND W. SNYDER is a First Lieutenant in the Air Corps, United States Army, Lowry Field, Denver, Colorado.

C. WINTHROP PAYNE may be addressed in care of N.K.P.M., Soengei Gerong, Palembang, Sumatra, N.E.I.

J. ELMER THOMAS, petroleum analyst of Fort Worth, Texas, who went to Washington in June as a consulting advisor to the Office of Price Administration and Civilian Supply, has been named associate price executive and associate chief of the Fuel Section, Price Administration.

M. M. KORNFELD, consulting petroleum geologist, has moved from the West Building to 1818 Second National Bank Building, Houston, Texas. His paleontological laboratory is at 3015 Ruth Street, Houston. Kornfeld has opened a branch office for consulting work at 506 Guaranty Bank Building, Alexandria, Louisiana, with James Muslow as associate.

J. W. HUDDLE, associate professor of geology at the University of North Carolina, acted as field geologist for the Geological Survey of Alabama this summer, during the temporary absence, because of illness, of EDGAR BOWLES, staff geologist of the Survey.

CURTIS L. WILSON, for the past 20 years connected with the Montana School of Mines at Butte, Montana, and for the last 13 years professor of metallurgy and head of the metallurgy department there, has been appointed dean of the Missouri School of Mines and Metallurgy at Rolla, Missouri, succeeding WILLIAM R. CHEDSEY, who resigned.

R. V. HOLLINGSWORTH, who recently returned from graduate work in paleontology at the University of Chicago, has resigned his position in charge of stratigraphic and paleontological work in the Tulsa office of the Shell Oil Company, Inc., to become assistant professor of geology at the University of Tulsa.

L. R. LAUDON, has resigned as associate professor of geology at the University of Tulsa, to accept appointment as associate professor of geology at

the University of Kansas at Lawrence. He will handle beginning work, petroleum geology, and part of paleontology.

ROBERT HARLOW SMITH, consulting geologist, has changed his address to 863 Merrifield Street, S. E., Grand Rapids, Michigan.

W. P. CONWAY, JR., has changed his address from the Phillips Petroleum Company, Houston, Texas, to 2162 University Avenue, Bronx, New York City.

WILLIAM A. MCFADDEN, JR., is with the Standard Oil Company of Texas, Houston, Texas.

WILSON C. GIFFIN, who has been with The Texas Company in Caracas, Venezuela, may be addressed at 2320 Pasadena Avenue, Long Beach, California.

G. W. CRICKMAY, recently at Athens, Georgia, is at Puerto Cabezas, Nicaragua.

G. LESLIE WHIPPLE, who returned from India a few months ago, is again in Colombia, where he may be addressed at Apartado Nacional 2760, Bogota.

LINN M. FARISH has resigned his position as district geologist for the Magnolia Petroleum Company at Bismarck, North Dakota, and has accepted an appointment in the Civilian Technical Corps. The Civilian Technical Corps is an American group organized to work in England to aid in the war effort and the men are subject to recall whenever needed by the American Government. Farish is the author of a recent booklet, *The True Strength of America*. Mr. and Mrs. Farish have gone to Woodland, California, to visit his parents. Shortly after October 1, he will sail for England.

FRANK OLIVER MORTLOCK is on leave of absence from the Gulf Research and Development Company. His address is Industrial Department, U. S. Navy Yard, Cavite, Philippine Islands.

M. MILSTEIN, formerly with Geophysical Surveys, Ltd., at Melbourne, Australia, is located at 155 McPherson Avenue, Toronto, Canada.

MORGAN E. MCCASKEY, of Fort Worth, Texas, died by suicide, May 6, 1941.

DONALD B. WINES, recently district geologist for the Tide Water Associated Oil Company, is now geologist for the Central Petroleum Company, Inc., Wichita, Kansas.

Major BURTON HARTLEY may be addressed in care of the Military Department, A. and M. College, College Station, Texas.

WALTER M. CHAPPELL, of The Texas Petroleum Company, has returned to Colombia, after a vacation of 3 months in the United States. His address is Apartado Postal 159, Barranquilla, Colombia.

R. MAURICE TRIPP, recently with the Geotechnical Corporation at Dallas, Texas, is at 1521 East Street, Golden, Colorado.

CARLTON G. DINSMOOR has been called to active duty with the 79th Coast Artillery at Fort Bliss, El Paso, Texas.

CHARLES R. CANFIELD, formerly with the Union Oil Company of California, is geologist with the Stanolind Oil and Gas Company at Midland, Texas.

I. G. SOHN is with the United States Geological Survey, in the Mesozoic division, section of stratigraphy and paleontology. His address is Room 17, U. S. National Museum, Washington, D. C.

ADOLPH DOVRE, petroleum geologist and oil producer of San Antonio, Texas, was taken critically ill, July 2, shortly after returning from a visit with relatives and friends in Michigan, Wisconsin, and Minnesota where he attended the twenty-fifth reunion of his class at the University of Minnesota. A heart attack led to a blood clot in a large artery of the left leg above the knee, and amputation of that leg was necessary. Adolph has had a miraculous recovery and his friends anticipate his return to normal business activities in the near future.

W. W. HEATHMAN, of the Union Oil Company of California, has been transferred from Los Angeles to Wichita, Kansas, where he has charge of the new branch office, as manager of Kansas operations.

VIRGIL WINKLER has left Urbana, Illinois, to go to Venezuela, where he is in the geology laboratory of the Standard Oil Company of Venezuela, at Caripito.

CHARLES M. REED, recently with the General Geophysical Company at Houston, has accepted a position as field laboratory assistant with Core Laboratories, Inc., at Centralia, Illinois.

HENRY HOTCHKISS has returned from Basrah, Iraq, where he was geologist for the Basrah Petroleum Company, Ltd. He is at East River, Connecticut.

FIELD TRIP

WEST TEXAS GEOLOGICAL SOCIETY, FALL FIELD TRIP, SEPTEMBER 27-28

The 1941 fall field trip of the West Texas Geological Society will be taken to the proposed Big Bend National Park area. Ross A. Maxwell, regional geologist of the National Park Service, will act as guide. Vaughn C. Maley is chairman of the Society's field-trip committee. Those participating in the trip will register at the Holland Hotel, Alpine, Texas, the evening of September 26. The party will assemble at 8 A.M., Saturday, September 27, at Marathon, and that day will drive south through the Marathon basin to Persimmon Gap, Dog Canyon, and Santa Elena Canyon. Arrangements have been made with the Civilian Conservation Corps for the party to spend Saturday night at the Chisos Mountains C.C.C. camp. Sunday, the excursion will proceed to the Study Butte quicksilver mine, Terlingua, and Alpine. If rains should prevent the crossing of Terlingua Creek on Sunday, an alternative trip will be taken to the country southeast of the Chisos Mountains and from there the party will return to Marathon by the same road as that followed on the previous day.

A guide book containing maps and cross sections will be furnished to those registering. The registration fee has not yet been determined, but will not exceed \$3.00.

In order that adequate arrangements may be made in advance, all who intend to go on the field trip are urged to communicate with Vaughn C. Maley, Humble Oil and Refining Company, Midland Texas, by September 19.

ROBERT E. KING, *president*
West Texas Geological Society

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<p>G. H. WESTBY <i>Geologist and Geophysicist</i> <i>Seismograph Service Corporation</i> Kennedy Building Tulsa, Oklahoma</p>	
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Stanolind Oil and Gas Company

Meetings will be announced

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Editor - - - - - Robert C. Lafferty
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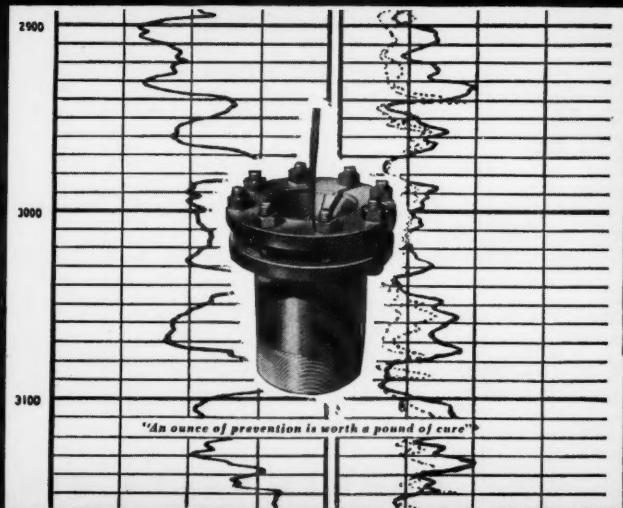
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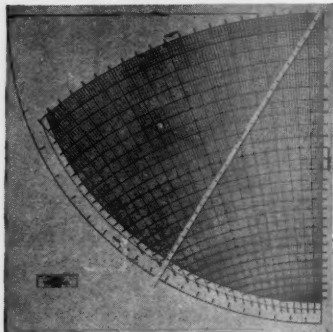


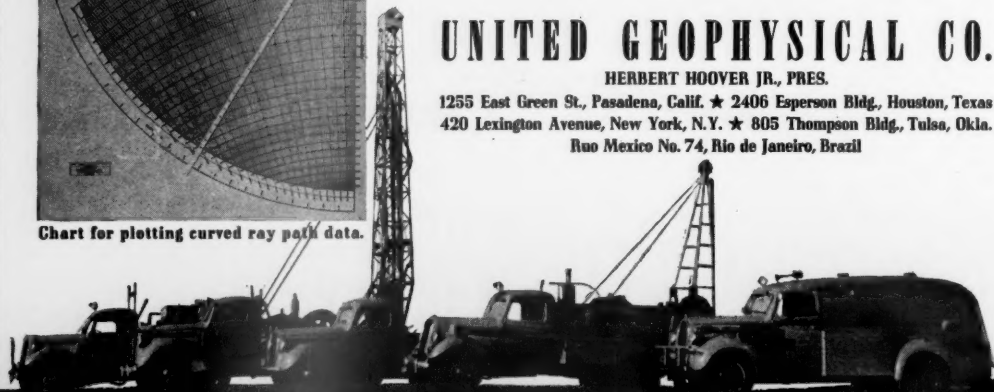
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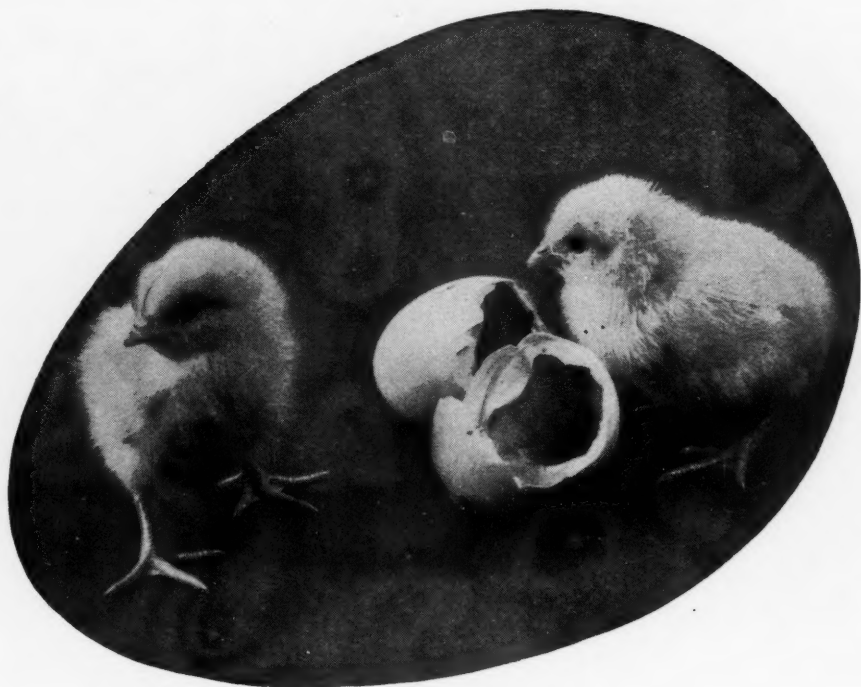
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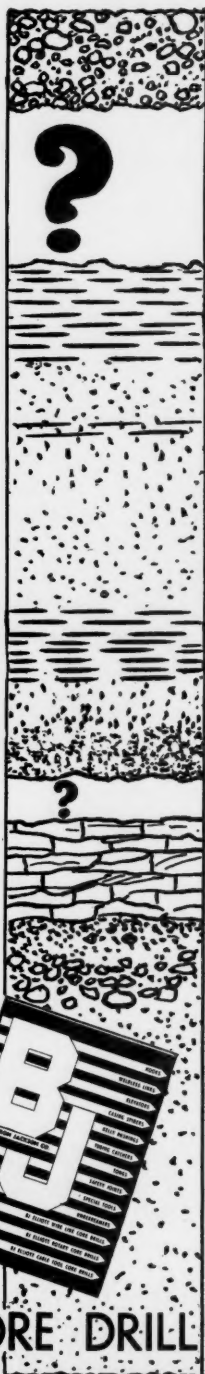
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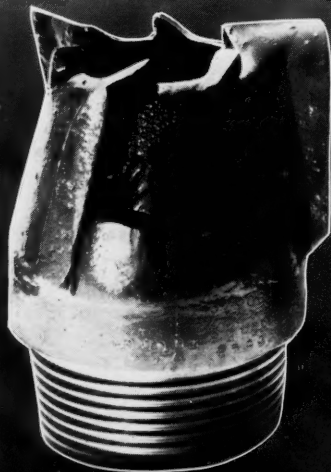
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